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THE USE OF AERIAL PHOTOGRAPHY IN THE  
STUDY OF WAVE CHARACTERISTICS IN THE  
COASTAL ZONE

Cecil M. McClenan, et al

Coastal Engineering Research Center  
Fort Belvoir, Virginia

January 1975

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20. Abstract (Continued)

Good aerial photos of waves shows that multiple wave trains are common in the coastal zone. The relative importance of the various wave trains is changed by refraction and shoaling. The breakers, most prominent in the shore zone, often result from long, low swell, which is hardly discernable against the background of shorter waves a few hundred meters from shore. The generation of solitions and the regeneration of breakers which have crossed bars may lead to a breaker which is shorter than the period of the swell responsible for the breakers. Cylindrical waves radiating outward from rocks or shoals which penetrate the surface are formed from long-crested waves coming from the open sea. A wave pattern which appears random and chaotic when viewed on photos taken at a low elevation may appear to be highly organized when viewed at an elevation over 5,000 feet.

This report discusses conditions which favor good aerial photos of waves and presents examples of many phenomena in wave behavior which are best seen from the perspective afforded by a high elevation.

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## PREFACE

This report is published to assist coastal engineers in the use of aerial photography for the study of ocean wave phenomena. The work was carried out under the wave mechanics research program of the U.S. Army Coastal Engineering Research Center (CERC).

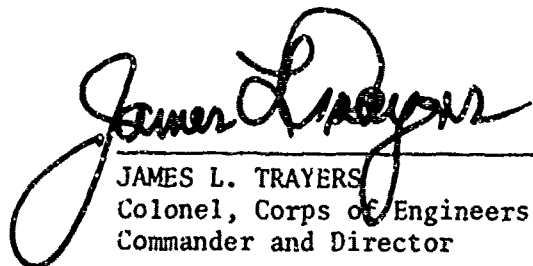
The report was prepared by Cecil M. McClenan, a CERC Oceanographer, and Dr. D. Lee Harris, Chief, Oceanography Branch, Research Division, CERC.

Special appreciation is extended to Mr. Edward F. Thompson for his aid in producing useful wave spectra analyses and for his constructive comments. Thanks are expressed to Messrs. Dennis W. Berg, Adrian J. Combe III, James H. Balsillie, and Morrison G. Essick of the CERC staff for providing many useful photos for the authors' review. Thanks are also extended to Mr. James T. Dayton for providing photographic services.

The sequence of photography revealing a constant sea state for a 42-minute period was provided by the National Aeronautics and Space Administration, Earth Observations Aircraft Program; the sequence of photos over the same location at varying altitudes was obtained during a study by Mr. Curtis Mason of CERC.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

  
JAMES L. TRAYERS  
Colonel, Corps of Engineers  
Commander and Director

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# THE USE OF AERIAL PHOTOGRAPHY IN THE STUDY OF WAVE CHARACTERISTICS IN THE COASTAL ZONE

by

*Cecil M. McClenan and D. Lee Harris*

## I. INTRODUCTION

Waves which travel across the ocean and ultimately break in the surf zone are of great concern when the coastal engineer initiates the design of coastal structures. The most satisfactory information about wave characteristics commonly available is obtained from recording wave gages which give the elevation of the free surface or the pressure at a fixed point as a function of time. Data on the two-dimensional geometry of the wave pattern and the direction of wave approach are also needed to estimate the forces which the wave will exert on the beach or nearby structures. Information, not provided by gage records, is generally inferred from theoretically and empirically derived concepts about wave mechanics. Occasionally an array of wave sensors is used to provide more details about the wave geometry. Even with an array of sensors, however, recourse to rather specific hypotheses about the wave field is generally essential to a complete interpretation of the record.

A problem with the wave records from a single gage is that many different wave conditions can lead to similar wave records. For example, a complex wave record may have resulted from a complex waveform arriving from a discrete direction, or from a combination of simple waves arriving from many directions. The recorded waves result from near linear refraction of wind-generated waves from the open sea. Some of the waves may have been generated by passing ships; other waves may have resulted from reflection or nonlinear transformation of primary waves. The wave gage record from a single gage provides little information about the geometry of the wave field. Most of the missing information is estimated by invoking a hypothesis about the two-dimensional characteristics of the wave field with little attempt at verification.

Aerial photos can provide a wealth of information on wave geometry without appeal to any theoretical concepts. The redundancy of overlapping information obtained by combining aerial photos with wave gage records and theoretical concepts greatly reduces the uncertainties involved in the interpretation of data from a single source. In many cases it is evident from the photos that some commonly applied concepts about wave characteristics in the coastal zone are incorrect. These are discussed in Section VII after some photographic evidence has been introduced.

The most common waves in the coastal zone are generated by the wind over the open sea and modified by refraction, shoaling, reflection, diffraction, scattering, and perhaps other nonlinear processes.

Many wave characteristics may be revealed by aerial photos. The characteristics of greatest interest in this study are:

- (a) Wave direction in the breaker zone.
- (b) Wave direction in the offshore zone.
- (c) Wavelength between successive crests.
- (d) Wave height.
- (e) Typical crest length to wavelength ratios.
- (f) Frequency of the simultaneous presence of more than one wave train.
- (g) Relation of wave refraction to distance from shore, water depth, and influence of submarine canyons, large bays, sharp changes in shorelines, and tidal currents.
- (h) Wave diffraction as influenced by distance from structure or island.
- (i) Reflected waves.
- (j) Modifications of wave-coast geometry not listed above.

Most of the photos examined early in this study had been obtained for studies of land features. Often the exposure settings had been determined for highly reflective sand beaches. As a result, they were underexposed for the highly absorbing water surface, and showed little detail about the waves. In many photos the only discernable waves were breakers, where foam increased the reflectivity of the water.

In some of the early photos, the exposure was suitable for revealing wave characteristics over no more than 10 to 20 percent of the image. This was especially true for the margin around sunspots in the film. Later, several flights were obtained through the cooperation of the National Aeronautics and Space Administration's (NASA) Earth Observations Aircraft Program in which the exposure for one or more cameras was selected with the goal of obtaining good wave photography.

The wave patterns shown in the photos used in this report are typical of the wave patterns found in all of the photos examined. Two sequences, however, were obtained especially for this report. These are Figures 3 through 7, illustrating the effect of increasing elevation to obtain a better perspective for a complex wave pattern, and Figures 34 through 37, to show the stability of a given wave pattern in time. The individual photos in these series are similar to most other photos obtained under similar conditions, but the sequences of photos of the same sea state with systematic changes in altitude or time are unusual.

The selection of photos to be included was based on the clarity with which typical wave features are shown. Some of the photos also contain slicks, e.g., Figure 21. Others reveal evidence of sediment transport. This report, however, is concerned with the unique ability of aerial photos to document the geometrical pattern of waves in coastal waters; no attempt is made to explain other features in the photography.

## II. PREVIOUS STUDIES OF WAVE PHOTOGRAPHS

During World War II, aerial photos of waves were combined with wave shoaling analyses to obtain estimates of bottom topography in areas where little information about bottom topography was available (U.S. Naval Photographic Interpretation Center, 1944). These techniques may still be used in areas where urgently needed hydrographic data is outdated or unavailable (U.S. Naval Photographic Interpretation Center, 1960; and Polcyn, Brown and Sattinger, 1970).

Sawyer (1949), Dickerson (1950), Marks and Ronne (1955), Schumacher (1952), Cote, et al. (1960), Korshunov (1963), and Zdanovich and Sharikov (1966), derived values for wave heights through the use of aerial photography. Although useful estimates of wave heights can be obtained from stereo-photos, this procedure is too costly for extensive use in the collection of wave records. Aerial photos of waves have also been studied by Ward (1952) and Emery (1958, 1963). The majority of wave studies were made for the determination of depth (Crooke, et al., 1951; Johnson, 1949; Moffitt, 1953; Polcyn and Sattinger, 1969).

Review of earlier studies provided a preliminary definition of the photographic and physical conditions required for the production of good wave photos. Suggestions for enhancing wave visibility fell into three categories: sea state, photo scale, and sun angle.

The sea state should contain at least one train of swell with substantial height so that the crests will be distinguishable in the photo. In depth studies, it is preferable to have only one prominent wave train. Crooke, et al. (1951) and Moffitt (1953) stated that a light wind chop over swell adds texture to the sea surface and thereby enhances the swell pattern. The roughening of the water surface also aids in reducing mirror-type reflections of the sunspot during times of high sun angles.

The suggested photo scale varied widely depending on the particular objective of each study. The largest scale used, 1:600 by Sawyer (1949), was to achieve sufficient accuracy for obtaining wave heights in the surf zone. The smallest scale suggested was 1:15,000 by the U.S. Naval Photographic Interpretation Center (1944); and Crooke, et al. (1951) in attaining wavelength measurements for calculating depth.

In consideration of sun angle, most investigators preferred low angles. A low sun angle causes the wave crest to be highlighted by the

reflective and shadow effects (Fig. 1). However, for effective high-lighting, the waves would have to be traveling in a direction such that their crests were aligned nearly perpendicular to the approach of the sun's rays. If the wave crests were oriented parallel to the direction of the sun's rays, the reflective and shadow effects would not be realized and the wave crest would not be highlighted. The effect is shown in Figure 2.

### III. CRITERIA FOR AN "IDEAL" PHOTOGRAPH OF WAVES

The criteria for producing "ideal" wave photos were partly from the review of earlier reports on this topic discussed previously, and partly from an examination of the exceptionally useful photos obtained during this study, primarily with the cooperation of the NASA Earth Observations Aircraft Program.

#### 1. Sea State.

In agreement with earlier studies, waves of desirable length and height must be present, but as depth determination was not the primary objective of this study, the existence of two or more wave trains was not regarded as undesirable. The earlier suggestion that a local wind sea adds texture to the sea surface and prevents the mirror-type reflection during high sun angles has been confirmed.

#### 2. Optimum Scale.

Scales within the range of 1:10,000 to 1:130,000 have been found to provide enough detail for obtaining many of the desired wave characteristics. However, these scale ranges are not proposed as absolute limits. It is important to have at least 20 wavelengths of the longest wave train of interest in the photo. This will usually provide enough information on a particular wave train for general wave studies within the coastal zone. A decrease in scale may be required when information on large wave fields is needed. Small-scale photography is needed for studies of refraction over shoal areas or when studying large wave fields moving across the ocean with long crests and wavelengths. Larger scales will be required when studying smaller areas, i.e., wave reactions in the surf zone and wave reflection from structures.

The importance of scale and the field of view is illustrated by a series of photos taken off the Texas coast near Corpus Christi Water Exchange Pass through Mustang Island. Organized wave patterns, for example, are not easily identified in a photo taken at an altitude of 50 feet (Fig. 3). The antiquated saying, "You can't see the forest for the trees," is clearly applicable to this photo because it was taken too close to the water surface.

Photos shown in Figures 3 through 7 were taken at nearly the same horizontal location but the altitude of each photo is double that of the preceding one, thereby halving the scale. From this series of photos,

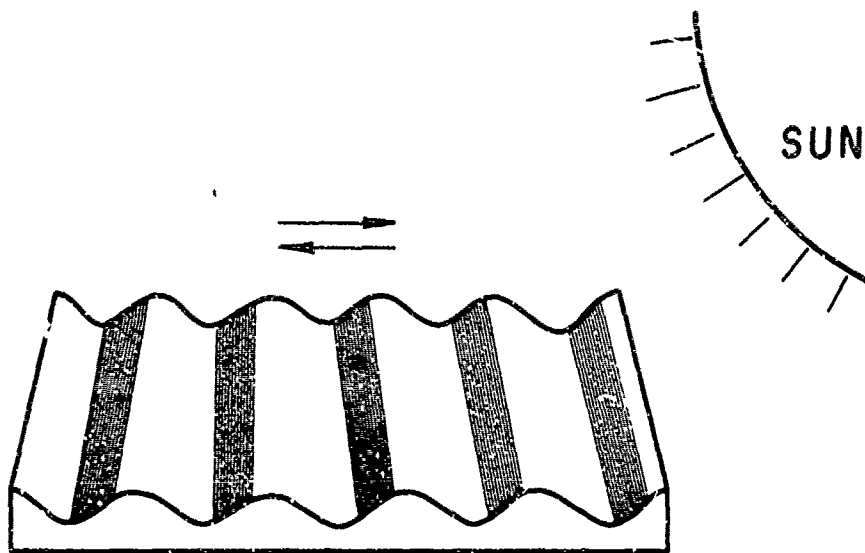


Figure 1. Wave crests alined perpendicular to tle sun's rays.

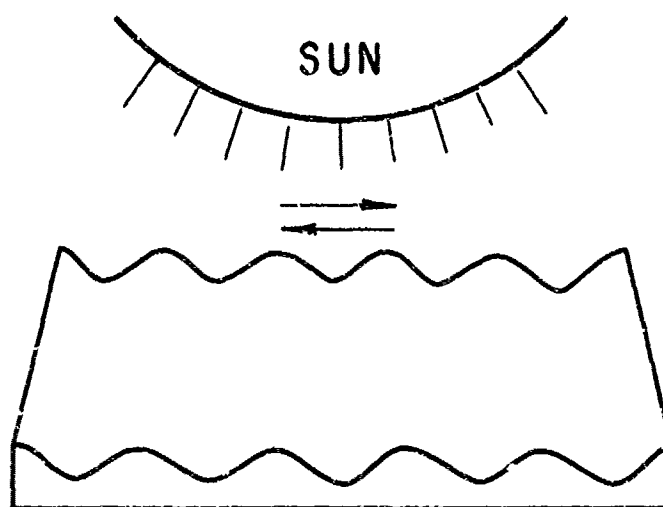


Figure 2. Wave crests alined parallel to sun's rays.

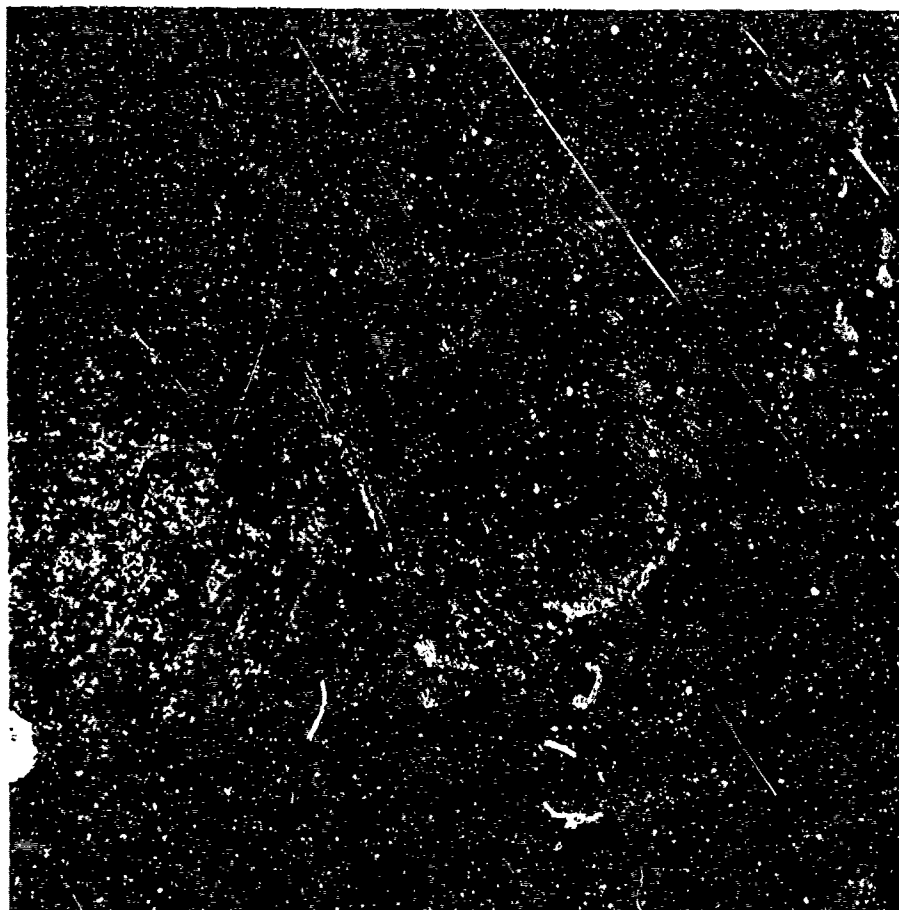


Figure 3. Gulf of Mexico, 3 miles offshore from Mustang Island near the Corpus Christi Water Exchange Pass, Texas. Photo taken on 23 July 1973 at an altitude of 500 feet. Photos in Figures 4 through 7 were taken on the same date at about the same location but at different altitudes.

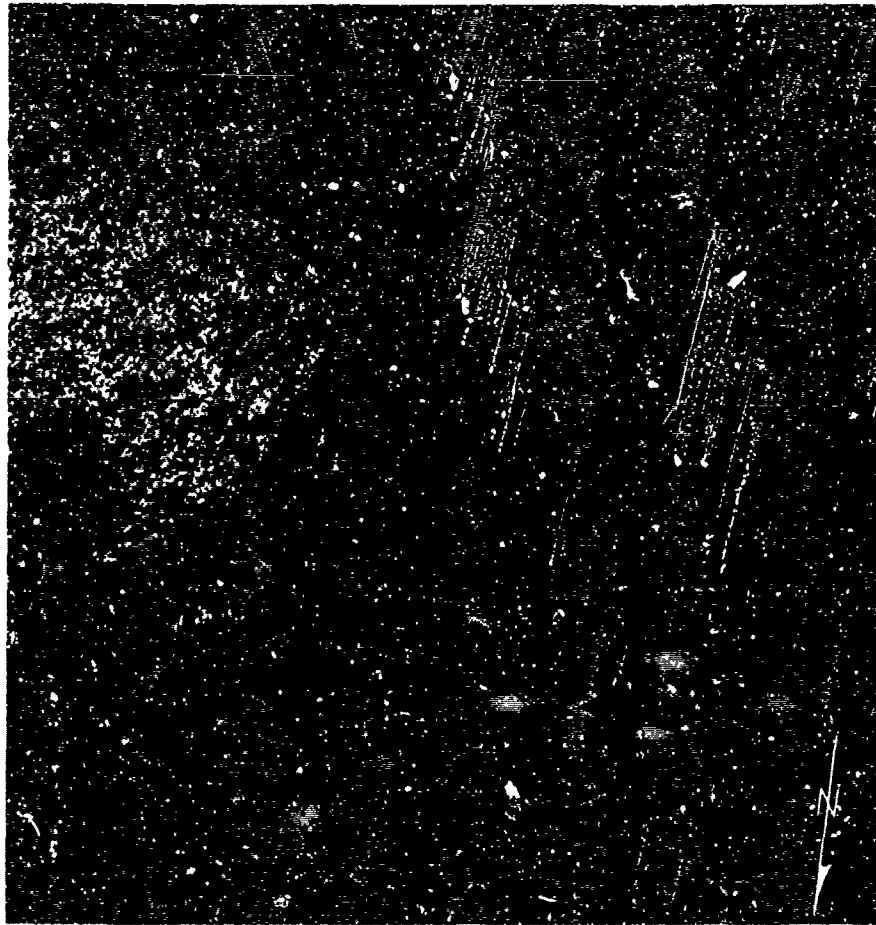


Figure 4. Photo taken at an altitude of 1,000 feet.

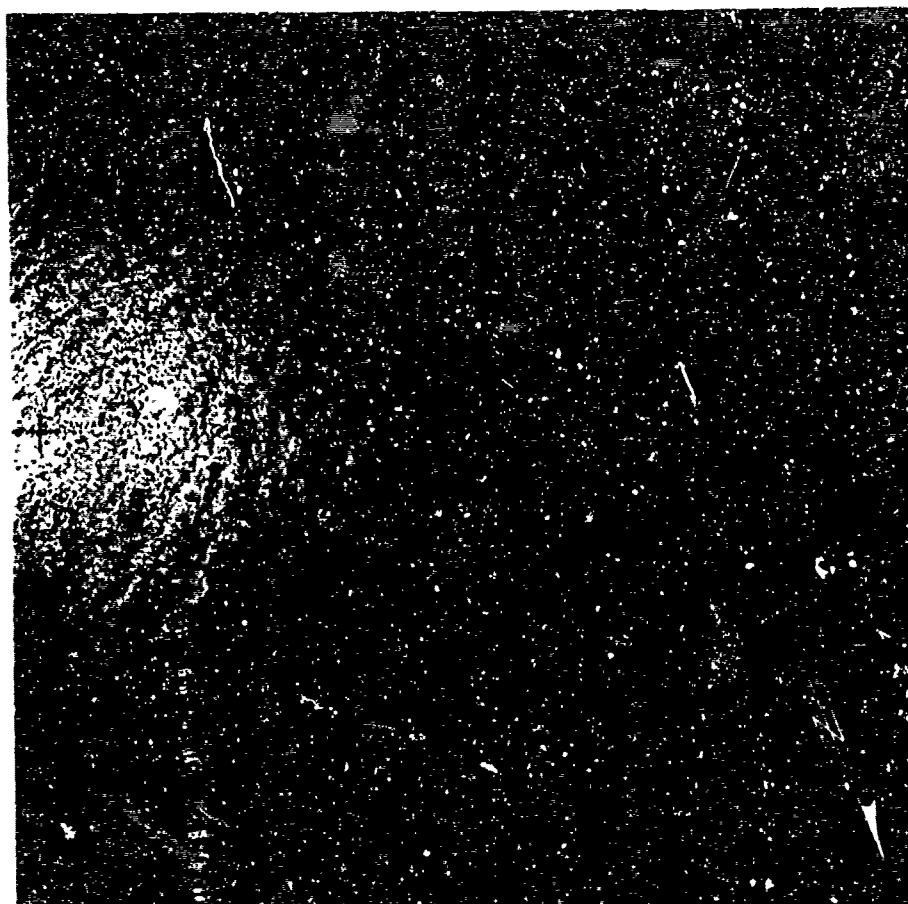


Figure 5. Photo taken at an altitude of 2,000 feet.

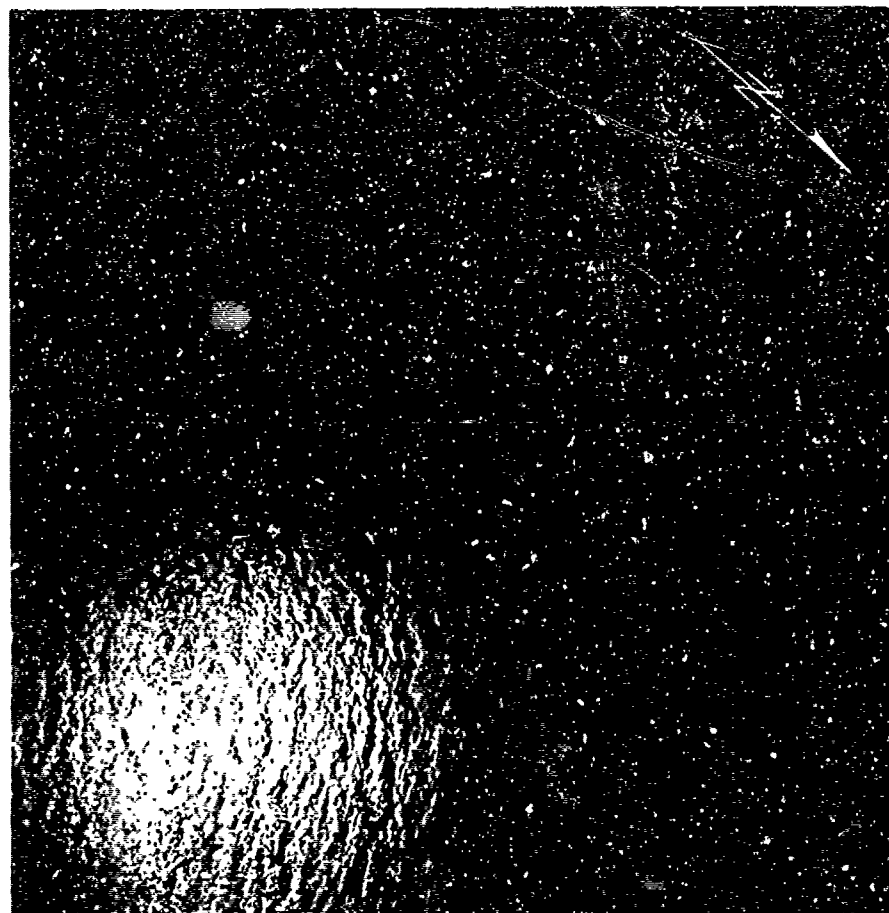


Figure 6. Photo taken at an altitude of 4,000 feet.

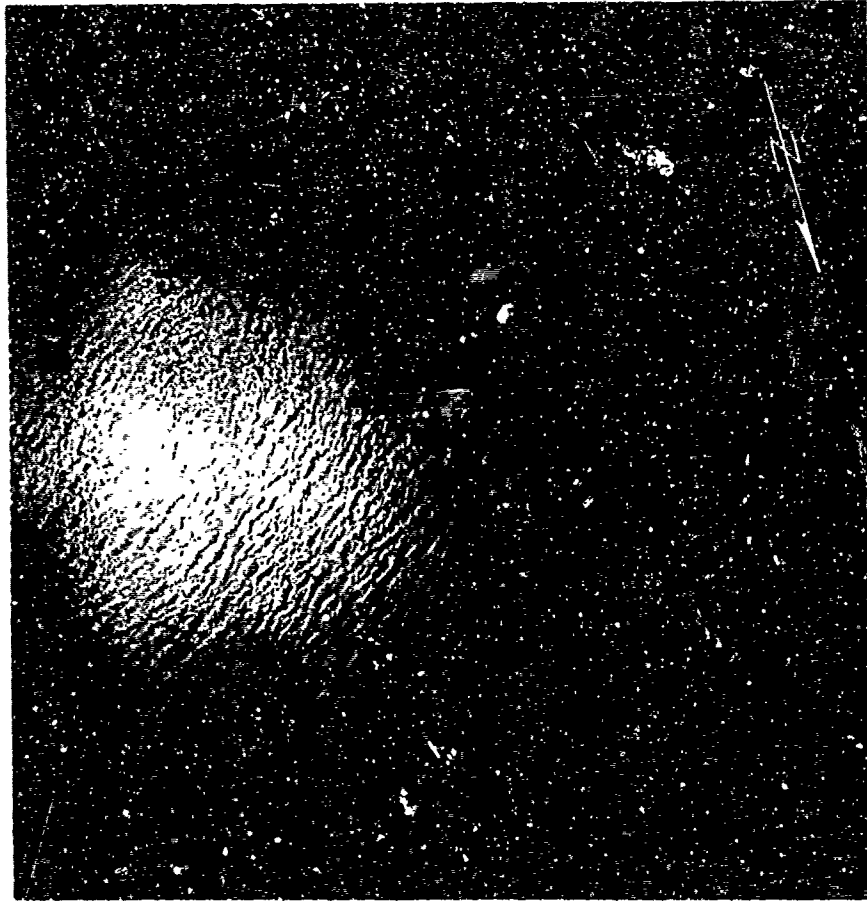


Figure 7. Photo taken at an altitude of 8,000 feet.

it can be seen that as the altitude is increased, the apparent wave organization increases. This tendency for photos of the sea to display more regularity of the sea surface as the elevation above the water surface increases is also noted by Kinsman (1965, p. 543). The appearance of increasing organization of the wave crest geometry increases up to some optimum altitude, limited by deterioration of the resolution of the wave crests.

A photo obtained on 70-millimeter film at an altitude of 65,000 feet over the California coast near Huntington Beach is shown in Figure 8. This altitude is near the upper limit of elevation for easily observing sea waves whose crests are aligned vertically on either side of the sunspot. If resolution were adequate on this small film format, further enlargement may provide more useful information about the waves. Notice in Figure 8 that the train of swell north of the sunspot has crests aligned in a nearly east-west direction, and that a train of shorter waves, with crests north-south can be seen both to the east and west of the sunspot. Both wave trains show refraction near the shore.

A photo (Harris, 1972) taken from the Apollo 7 spacecraft near the island of Biak just north of New Guinea at an approximate altitude of 100 miles is shown in Figure 9. When the upper left corner is enlarged (Fig. 10), waves with long crests and wavelengths are seen. The crest lengths in Figure 10 extend up to about 6 miles. Wavelengths of about 1,300 feet were also measured. This particular train of waves was generated by a typhoon about 1,400 miles from Biak. The photo in Figure 9 was taken with a hand-held camera by an astronaut using high resolution film. This type of photography should not be confused with that obtained by the Earth Resources Technology Satellite (ERTS). The ERTS imagery is obtained by a scanner. The scanner data is digitized, transmitted to a ground station, and then processed into images. These images do not have the resolution capability of the hand-held camera photos. Swell can be seen in some images with suitable enhancement, but never as clearly as in the photos shown in Figures 9 and 10.

The proper photo scale, as indicated from the previous examples, will provide noticeable improvement to wave recognition. The best scale for a particular train of waves is predominately a function of the wavelength.

### 3. Lighting and Exposure.

In accord with earlier studies, lighting and exposure is critical in producing wave photos of usable quality. Many previous investigators concluded that a low sun angle was best; however, for the purpose of this study a high sun angle was preferable and also, that the film should be exposed for the water surface. The reason for the high sun angle is illustrated by Figure 11, which is a schematization of the effect of the sunspot in enhancing wave trains, and by example in Figure 8. The high sun angle will provide information on wave trains moving in all directions, where a low sun angle would provide good enhancement only for



Figure 8. California coast near Huntington Beach. Photo taken  
31 March 1972 at an altitude of 65,000 feet (Courtesy of NASA).

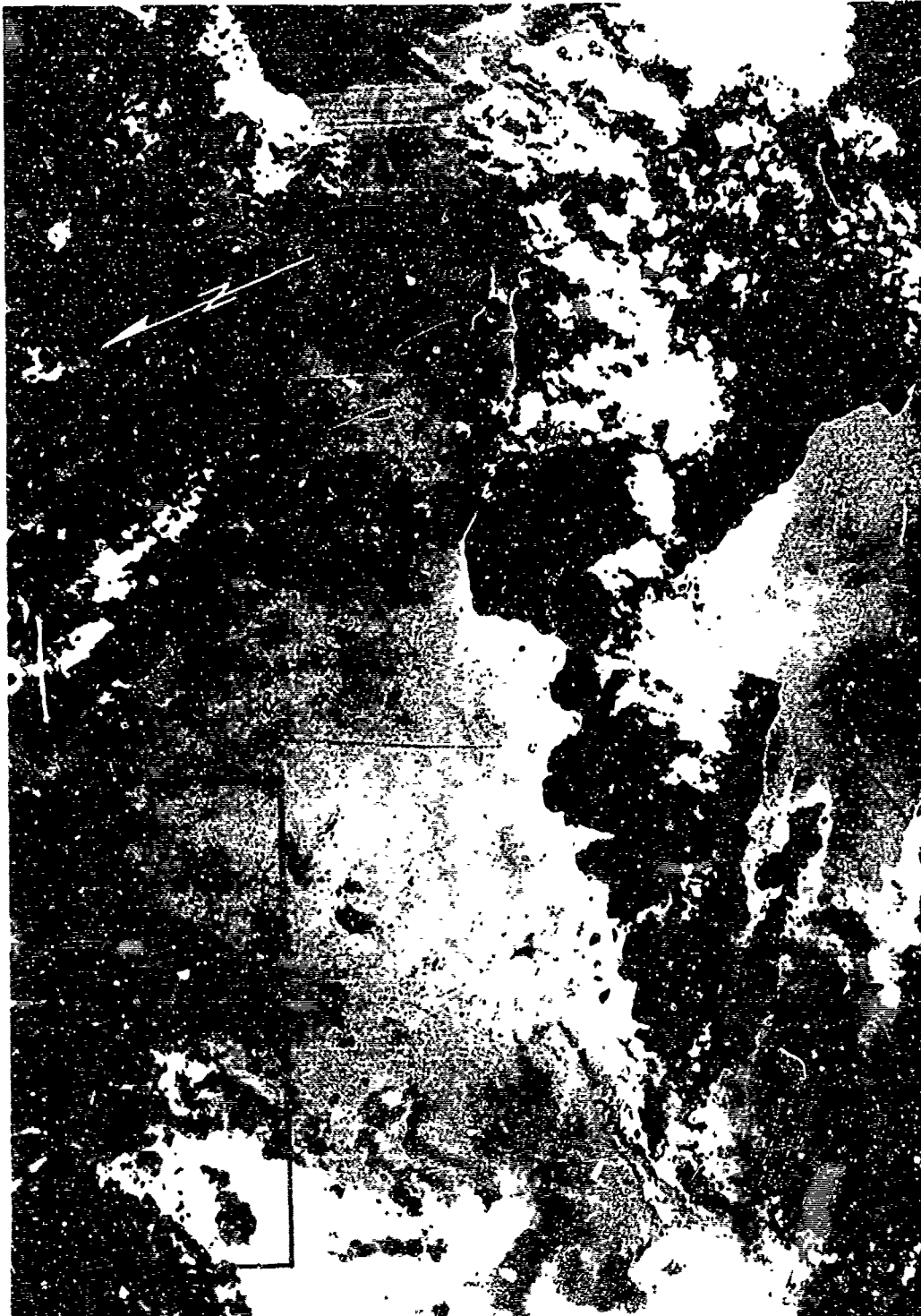


Figure 9. Island of Biak, located north of New Guinea. Photo taken from the Apollo 7 spacecraft on 23 October 1968 at an altitude of about 100 miles (Harris, 1972). Outlined section in upper left is enlarged in Figure 10.



Figure 10. Enlargement of outlined section shown in Figure 9, Photo shows straight long-crested waves with nearly the same wavelength and direction.

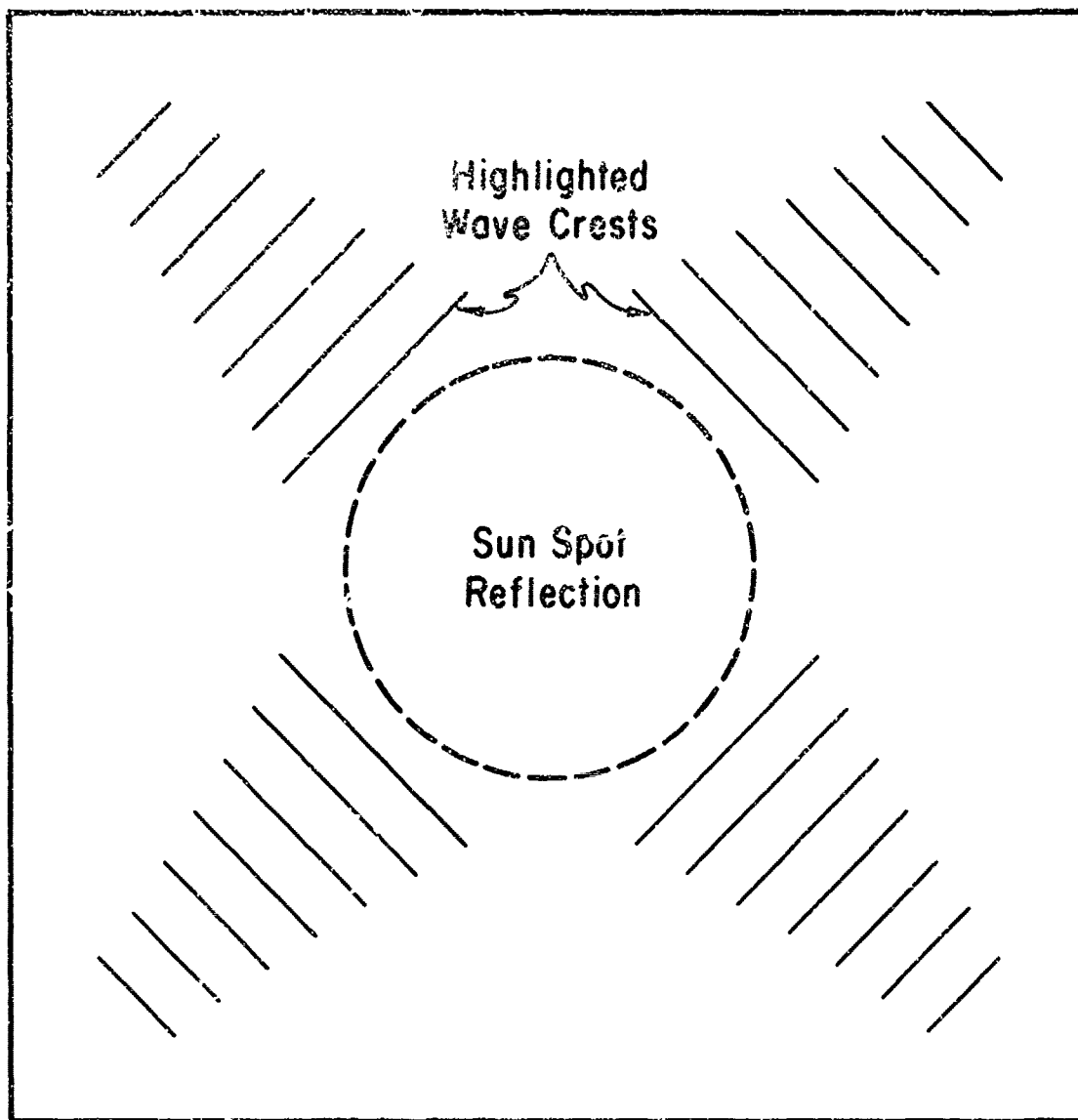


Figure 11. Schematic example of highlighted wave crests when alined tangent to the sunspot circle.

waves whose crests are nearly perpendicular to the sun's rays. With the high sun angle the sunspot reflection will be in the photo. Wave crests are highlighted where they are tangent to the sunspot circle. Aided by the sunspot, five separate wave trains may be detected in Figure 12, a black and white reproduction of a color infrared photo, which shows a section of the northern California coast just south of Crescent City.

In Figure 12, and with all the figures to follow, the different wave trains will be indicated on the photos by two parallel line segments signifying approximate crest alignment and wavelength, with an arrow extending from one of the line segments denoting the direction of wave travel. Difficulty in recognizing some of the indicated wave trains when looking directly at the picture is not unusual; they are often more visible when the picture is rotated. Duplication of a photo by an office copier may filter some wave trains from the photo, thereby facilitating the recognition of the remaining imagery.

The longer wavelength swells below the sunspot in Figure 12, indicated by the line segments at A, are easier to identify when the picture is rotated about  $45^\circ$ . A second train of swell with a shorter wavelength can be seen at B; another train of waves appears at C. A local sea with a very short wavelength is shown at D. Very short wavelength cylindrical waves seem to be radiating from a rock protruding from the sea surface at E. These waves are created by the scattering of wave energy from the other wave trains by the rock. This phenomenon will be discussed and illustrated later in Figures 25 and 26.

A photo (Fig. 13), taken during less than ideal circumstances, shows the mouth of the Tijuana River just north of the California-Mexico border. The photo was exposed to obtain detail in the lighter land-beach area and produced good definition of the dune line and vegetation behind the dune line. Exposing for the lighter land-beach areas produced water surfaces that are under-exposed and black. Since the sunspot cannot be observed, it is apparent that the photo was not taken during a high sun angle. However, Figure 13 does have a redeeming quality from a wave study standpoint—the breaker direction can be estimated from the streaks of foam caused by the breaking waves.

If certain photographic criteria are followed, it is clear from the examples presented that quality photos for use in wave studies can be obtained. A brief summary of these criteria are:

- (a) Sea state; waves of desirable length and height are present. Local wind chop adds texture to surface.
- (b) Optimum scale; dependent on the wavelength of the wave train to be studied. The appearance of wave-crest organization increases as altitude increases.

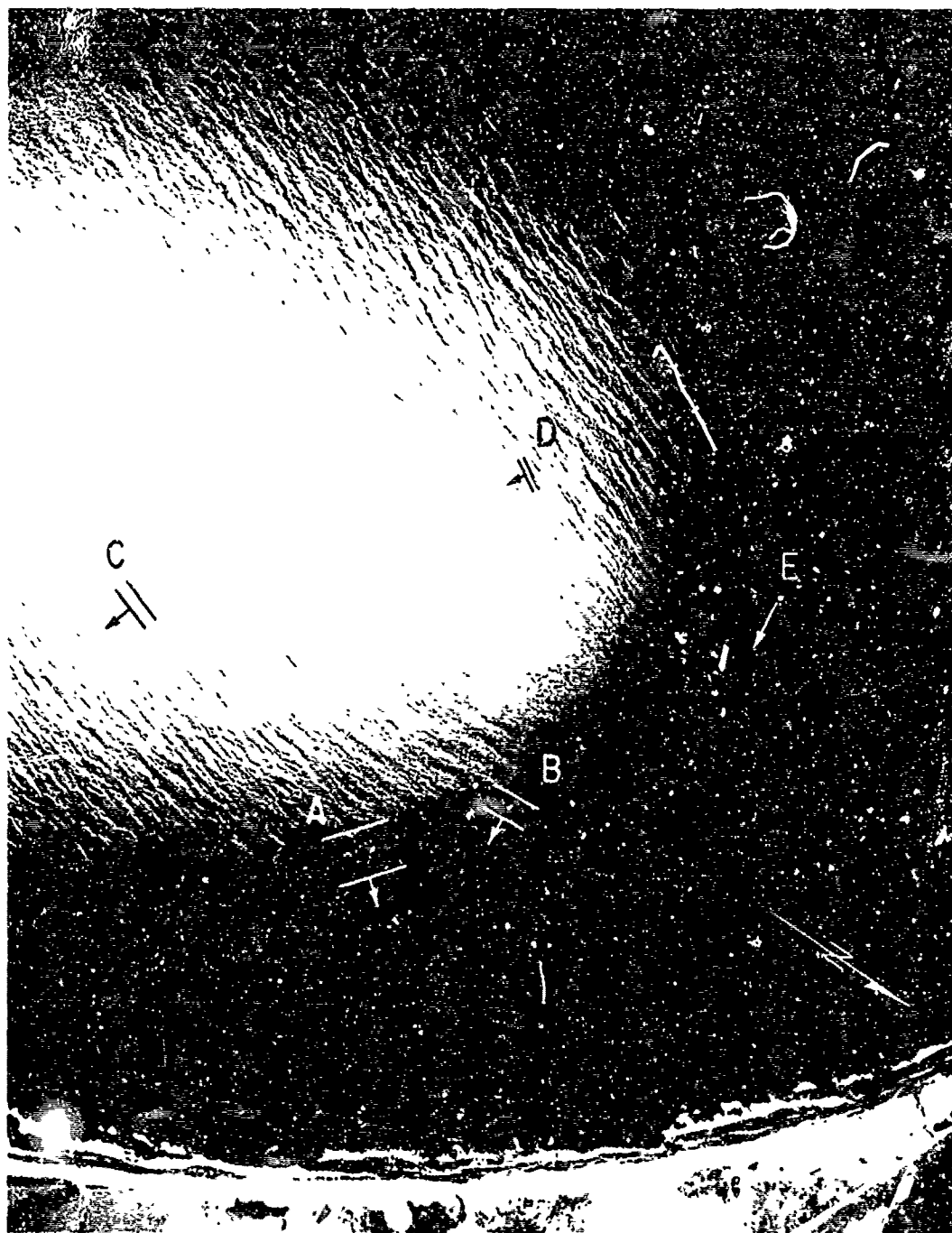


Figure 12. Pacific coast 3 miles south of Crescent City, California. Photo, taken 24 May 1972, shows wave-crest enhancement by having sunspot in the imagery. Photo is a black and white reproduction of a color infrared transparency (Courtesy of NASA).



Scale (Feet)  
0 200 400 800

Figure 13. Pacific coast at the mouth of the Tijuana River, California. Photo taken 20 December 1965. Example of poor photographic conditions to obtain wave information.

- (c) Lighting and exposure; high sun angles are preferred for wave-crest enhancement in all directions. The camera exposure should be exposed for the water surface.

#### IV. PHOTOGRAPHIC SEARCH

The search for ocean wave photos began in the various photographic files at CERC and later extended to the files of the National Ocean Survey, National Oceanic and Atmospheric Administration (NOAA) in Rockville, Maryland and the NASA Earth Resources Research Data Facility at the Johnson Space Center in Houston, Texas. The search produced only a small number of usable wave photos in comparison to the total number reviewed. Scarcity of high quality ocean wave photos results from the photography being taken at times when all three of the photographic conditions previously discussed were not present.

Most photographic flights were aimed at obtaining land and beach detail. Film exposure, when set for land-beach areas, produce severe underexposure of the relatively dark water surfaces. Another shortcoming of most available wave photos is that many of them represent unusually calm weather conditions. These conditions are satisfactory for comfortable flying, but they are not conducive to the production of desirable waves to photograph.

At the beginning of this study the authors found it difficult to mentally separate two or more wave trains. A method presented by Ward (1952) aided in the separation of the different wave trains. This method consisted of rotating a transparent sheet on which parallel lines were spaced about 10 to the inch over the photo. Ward stated that "... oftentimes to the astonishment of the viewer, order appeared out of a turbulent state of the sea that seemed devoid of orderly arrangement." As more photos were reviewed, reliance on this mechanical aid became unnecessary, and eventually all wave trains could be separated mentally. In some cases, certain wave trains became easily visible if the photos were rotated and observed at an angle other than vertical.

Attempts were made to enhance wave crests in selected photos. Such sophisticated instruments as the International Imaging Systems' Multiband Camera Film Viewer and the Spatial Data Systems' Datacolor System were used to improve wave-crest images in photos. These instruments did not provide suitable enhancement because of the large differential in gray scale caused by the sunspot in the photos. At times, duplicating a photo with an office copier filtered some of the detail and facilitated recognition of the remaining wave trains. However, the original transparencies always revealed as much or more detail than the positive prints. The best possible wave-crest enhancement was obtained by proper exposure and development processes in the photographic darkroom.

## V. WAVE CHARACTERISTICS IN THE COASTAL ZONE AS ILLUSTRATED BY AERIAL PHOTOGRAPHY

Aerial photography provides a perspective for wave behavior in the coastal zone not often available from land-based or shipboard observations. In this section, several photos which illustrate the modification of waves as they approach the coast from open sea are presented in each case. The photos shown in the figures are illustrative of the more than 40,000 photos examined in this study. In some cases the photos provide documentation of phenomena which have been long suspected; in others they seem to indicate that many of the commonly accepted hypotheses about wave behavior are not well founded. In particular, the sea surface in a photo taken at elevation of 5,000 to 15,000 feet, often appears to be more organized than many of the discussions of a random sea would imply. Possibly, some of this organization results from a tendency of the shallow depth of the coastal region to amplify some waves through an ill-defined resonance mechanism and to suppress others. Also, it is conceivable that the sea is everywhere complex but more highly organized than the discussions of the last two or three decades would indicate. Several phenomena are illustrated and discussed in this section. None of these cases is unusual but interest is heightened by finding photos to illustrate conditions which seem to contradict common assumptions or depict situations which have not been adequately described in scientific literature.

### 1. Wave System-Complex but Organized.

The photo in Figure 14, taken along the outer banks of North Carolina near the closed Swash Inlet, reveals a multiple wave train system. The longest wavelength swell is designated by the line segments and arrow at A. A second and third train of waves designated at B and C can also be observed. A local wind chop, superimposed on these wave systems, has aided in enhancement of the water surface. When this photo was originally observed there seemed to be a considerable amount of randomness to the wave structure; however, after separating the total wave structure into the different wave trains, a large amount of organization was apparent. If the wave system shown in Figure 14 was observed from a ship located offshore, the wave picture from such a low vantage point would probably be called random. This scene is also highly complex. A more simple system is often assumed when attempting to solve coastal problems.

### 2. Wave System Complex-Wave Train Dominating in the Offshore Area and in the Nearshore Breakers.

The photo in Figure 15 was also taken along the outer banks of North Carolina, just northeast of Swash Inlet. A group of long-period swell, A, dominates the wave picture offshore and is also contributing most of the energy in the breaker zone; participating in the breakers is a second train of short-period swell, B. A third wave train, C, which



Figure 14. Multiple wave train system offshore from Swash Inlet (closed), North Carolina. Photo taken 7 April 1968.



Figure 15. Three wave trains revealed northeast of Swash Inlet, North Carolina.  
Photo taken at 1325 hours EST on 25 April 1968 (Courtesy of  
National Ocean Survey, NOAA).

has a negligible effect on the breakers, and has a shorter wavelength than the other two wave trains, can be detected coming from the ocean area in the upper left of photo (Fig. 15).

The coastline in Figure 16 is located 10.5 miles southwest from the coastline in Figure 15. The photo in Figure 16 was taken 4 minutes after the one in Figure 15. Since the coastline in this area is relatively straight between the two photos, as expected, the wave picture is nearly the same. The same wave trains are detected traveling in about the same direction and causing a similar breaker scene.

The photo in Figure 17 shows the coast of Lake Michigan, 2 miles southwest of Michigan City, Indiana, and reveals three distinct wave trains caused by two groups of swells and one group of sea waves. The longer-period swell, A, coming from the upper right corner of the photo dominates both offshore and in the breaker zone. A shorter-period swell, B, coming from the upper left corner of the photo, most easily seen just offshore of the center of the photo also contributes energy into the breakers. A train of local sea waves, C, is moving from left to right across the photo. A line drawn perpendicular to the shorter-period swell crests, B, and extended across the lake, indicates an approximate fetch and decay distance of 40 miles for this particular wave train. This shows that fetch and decay distances within the Great Lakes, even though relatively short when compared to those in the open ocean, are sufficient to produce multiple wave train systems.

3. Wave Train Dominating in the Offshore Area is Different from the Wave Train Dominating in the Nearshore Breakers.

Figure 18 (Harris, 1972) shows a section of the California coast near Point Mugu and reveals that the train of waves, A, dominating in the offshore region arrives from a direction near the upper left corner of the photo. Another wave train, B, coming from the upper right corner dominates in the area about 1,000 feet offshore as it begins to shoal. However, the wave train dominating the breakers, C, is a train of long-period swell, with a very low wave height in deep water, but shoals substantially before breaking.

A section of the Atlantic coast of New Jersey, north of Cape May, is shown in Figure 19. In this photo a local sea, A, moving from right to left, dominates the offshore area. However, the breaker zone is dominated by a train of swell, B, approaching along a line nearly perpendicular to the shore.

The photo in Figure 20 shows the Atlantic coast just north of Ocean City, Maryland. As in Figure 19, the offshore region is dominated by a train of sea waves, A, with direction from left to right across the photo. Again, the breakers are dominated by a train of swell, B, approaching the coast from directly offshore.



Figure 16. The same three wave trains revealed in Figure 15 are seen in this photo. Photo taken just northeast of Drum Inlet, North Carolina at 1329 hours EST, 25 April 1968. This location is 10.5 miles downcoast from that of Figure 15.



Figure 17. Multiple wave train system along the Lake Michigan coast, southeast of Michigan City, Indiana. Photo taken 4 November 1966.

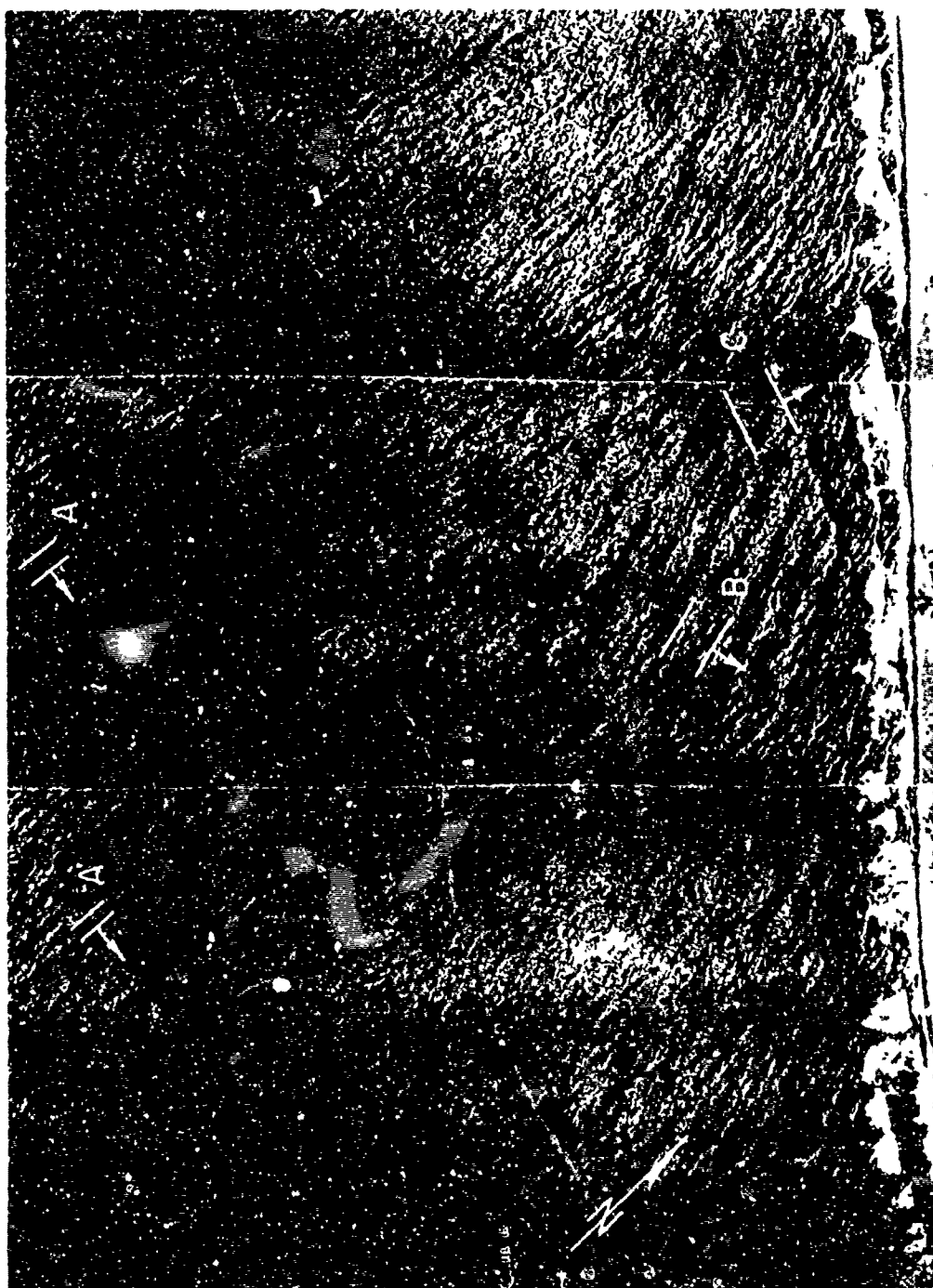
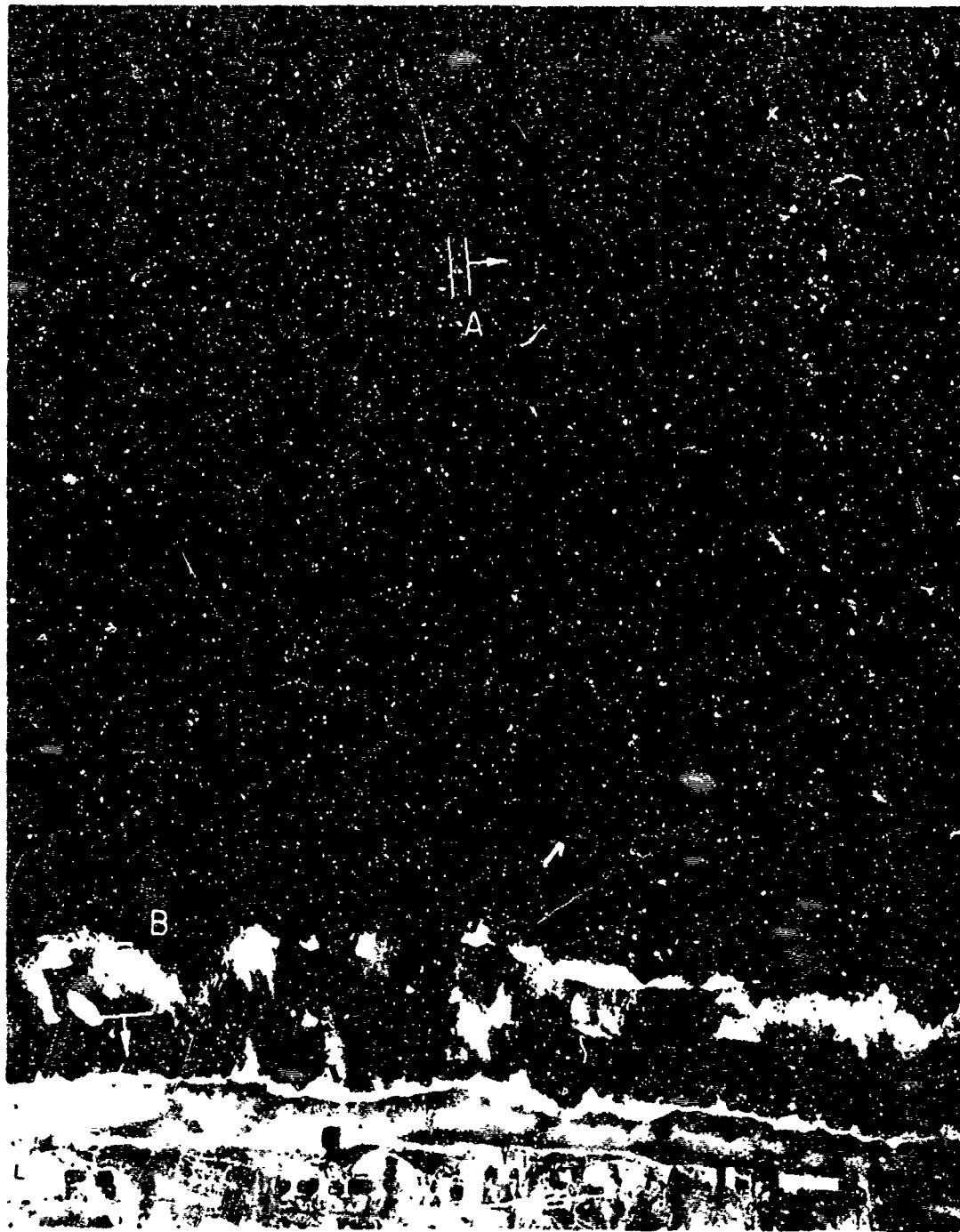


Figure 18. Site of CERC Prototype Experimental Groin (PEG) near Point Mugu, California (Harris, 1972).



Figure 19. Atlantic Ocean side of Cape May, New Jersey. Photo taken 14 March 1962. The wave train dominating the offshore, A, is not the wave train dominating in the breakers, B.



Scale (Feet)  
0 200 400 600

Figure 20. Atlantic Coast 6 miles north of Ocean City, Maryland. Photo taken 23 March 1962. The wave train dominating offshore, A, is not the wave train dominating in the breakers, B (Courtesy of U.S. Navy).

#### 4. Intersection of Two Wave Trains Near Shore.

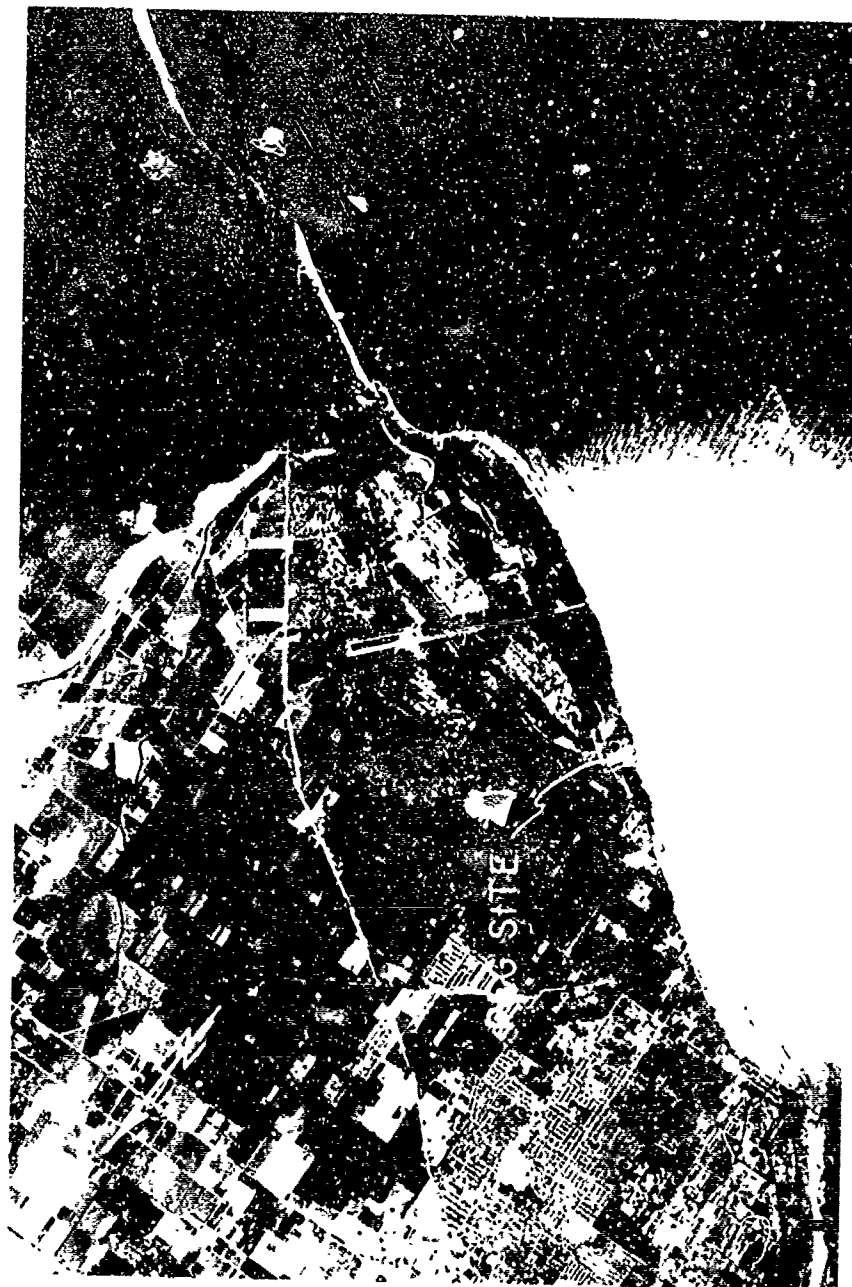
A photo of the California coast near Point Mugu taken at an altitude of 60,000 feet on 9-inch format film is shown in Figure 21. The photo shows trains crossing as they proceed into shallow water. The large film format provides adequate resolution in the nearshore area when substantially enlarged. In Figure 22, which is an enlargement of the area near the CERC Prototype Experimental Groin (PEG), the crossing wave trains are shown quite well. One train, A, approaches shore from the top of the photo while another, B, approaches from the upper left. Near the coast, the intersection of the two trains form streaks of high, short-crested waves which are aligned nearly perpendicular to the shoreline. Adjacent to these streaks of waves with short crests and increased heights are streaks where wave height is diminished. The streaks where the height is increased appear where the wave crests of the two trains are nearly in phase. The streaks of low-wave heights appear where the crests of the individual wave trains are nearly of opposite phase. Many node (high amplitude) and antinode (low amplitude) areas along this section of coast can be observed, and are indicated in Figure 22.

The reason these crossing trains of swell produce nodal streaks that are so pronounced and near symmetric is that they have nearly identical periods. One hypothesis of such a condition is that the two trains of swell may have been originally members of the same wave train, and were divided into two separate trains as they passed the nearby offshore islands of Santa Rosa and Santa Cruz. Following the separation, each wave train was then refracted across the path of the other nearshore to form the interaction shown in Figure 22. The occurrence of a similar wave train division was reported for this location by Emery (1958).

#### 5. Transformation of a Wave Train as it Breaks into Higher Frequency Components.

The photo in Figure 23 was taken from a light plane and shows the coast of Oahu in the Hawaiian Islands. A part of Waikiki Beach is covered in the lower right corner of the photo. This part of the photo and parts of the offshore area are under some cloud cover, causing a darker appearance. A train of long-period swell can be seen approaching the coast from the upper left part of the photo. At various locations just inside the breakers, higher frequency components of the original waveform can be observed. A depression in the sea floor is also detected just shoreward of the arrow in Figure 23. This depression is revealed by the arcing of the wave crests due to the increase in wave speed in the local area of the depression.

The photo in Figure 24 was taken about one-half mile southeast of Waikiki Beach; it shows the secondary waves which were caused by original, long-period waveforms passing over an offshore coral reef beneath the breakers.



Scale (Feet)  
0 5000 10,000

Figure 21. California coast in the vicinity of Port Hueneme and Point Mugu. Photo taken 4 April 1971 at an altitude of 60,000 feet on 9-inch format film (Courtesy of NASA).

A

B

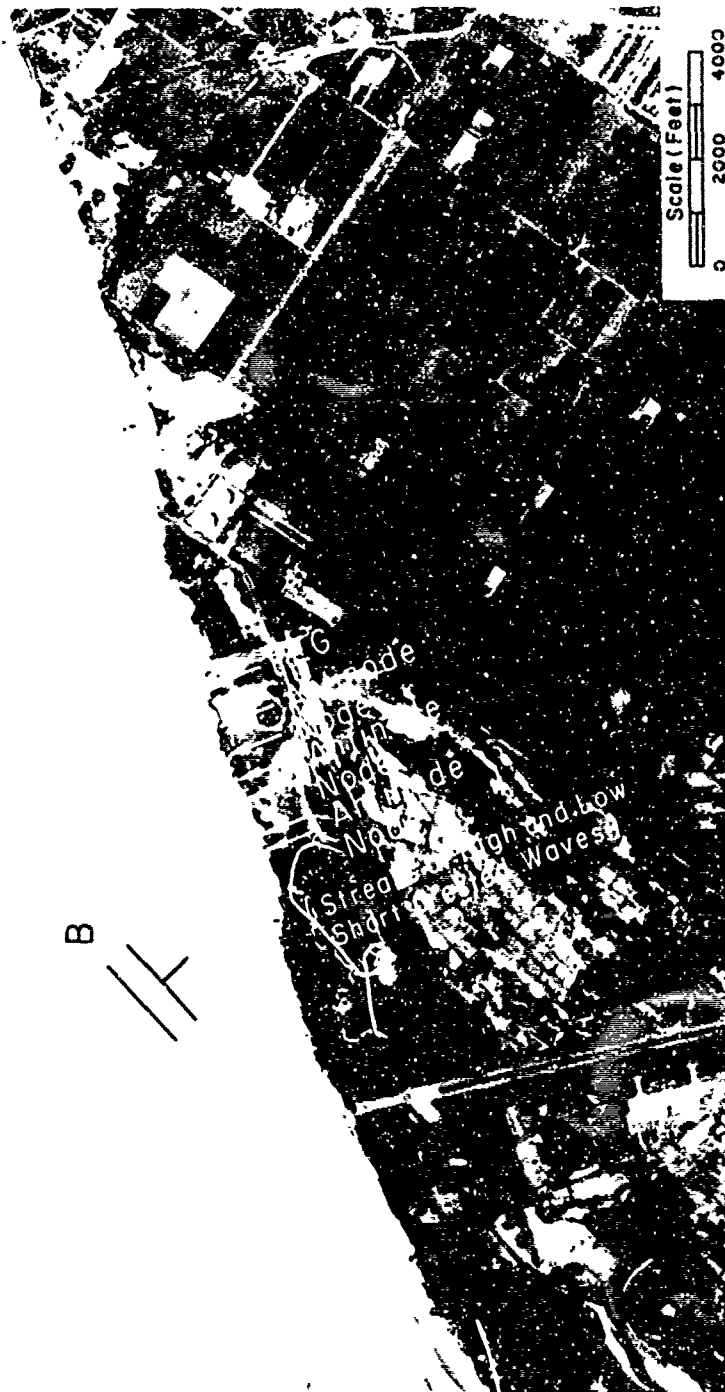


Figure 22. Enlargement of Figure 21 in area of the CERC Prototype Experimental Groin (PEG) site. Note streaks of high and low short-crested waves, caused by the intersection of two trains of swell.



Figure 23. Coast of Oahu near Waikiki Beach. Long-period swell moving over shoal area causes the wave energy to separate into higher frequency components. Shoreward of the arrow, the crest is arcing toward shore as that part of the crest moves over a depression in the sea floor (Courtesy of James R. Walker, University of Hawaii).



Figure 24. Coast of Oahu, southeast of Waikiki Beach. Note formation of secondary waves as long-period swells move over a shallow reef (Courtesy of James R. Walker, University of Hawaii).

#### 6. Waves Reflecting from Offshore Obstacles and Groins.

Figure 25 reveals waves coming from a northwesterly direction and striking Castle Rock, located off the California coast near Point Saint George. The photo shows short cylindrical waves radiating from Castle Rock in response to short-crested, but longer waves approaching from the northwest.

Another photo taken along the northern California coast is shown in Figure 26. Wave reflection is taking place near Sister Rocks off the coast from Midway Point. The original wave train is coming from the upper right part of the photo. As the waves strike the offshore rocks, higher frequency components are scattered outward in a circular pattern. Similar but less distinctive cylindrical-radiating waves may be seen in Figure 12.

A photo revealing an interesting reflection pattern is shown in Figure 27. The site is along Rockaway Beach, Long Island, New York. A train of short waves approaching the beach from the southwest is being reflected from the groins and onto the beach just west of the groins.

#### 7. Wave Diffraction.

The Channel Islands harbor breakwater off the coast of California is shown in Figure 28. Notice a train of waves coming from the upper right part of photo, striking a breakwater and producing a diffraction pattern around the breakwater tips. Since the photo was taken to obtain wave detail, parts of the beach are "bleached out." The breakwater is doing an excellent job of protecting the harbor entrance from the waves.

Figure 29 shows a breakwater off the entrance to Ventura Marina on the California coast. In this photo, long-crested swell, A, approaches the shoreline at an angle of about  $45^\circ$ . A second, shorter wavelength, wave train, B, approaches from the upper right part of the photo. Notice the local wind chop on the water surface, and how it enhances the visibility of the water surface; also that this particular breakwater does not protect the harbor entrance from the large waves coming from the upper left part of the photo. The suspended sediment seen here is being moved past the jetty tip at the harbor entrance and into the mouth of the harbor.

#### 8. Simple and Complex Refraction.

Figure 30, taken along the California coast in the vicinity of Point Mugu, shows a train of waves coming from the upper right corner of the photo and refracting through an approximately  $40^\circ$  angle before they break along the coast.

A photo taken along the east bank at the mouth of the Cape Fear River, North Carolina, is shown in Figure 31. In this photo, a more complex refraction pattern over the Bald Head Shoal area is taking place.



Scale (Feet)  
0 1000 2000 3000

Figure 25. Radial wave patterns formed by waves being reflected from Castle Rock offshore from Point Saint George, California. Photo taken on 24 May 1972 (Courtesy of NASA).

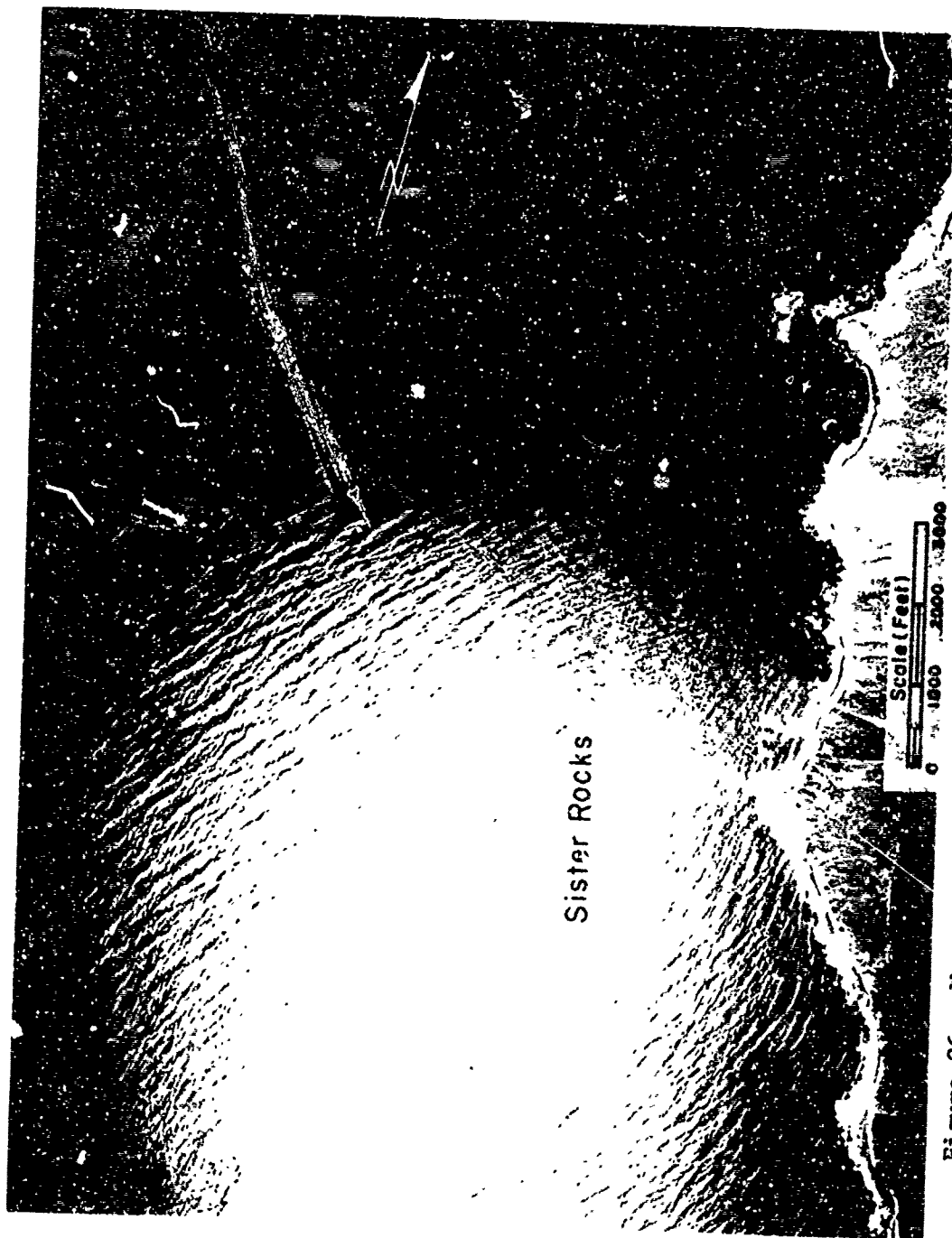


Figure 26. Waves reflecting from Sister Rocks, Midway Point, California.  
Photo taken 24 May 1972 (Courtesy of NASA).

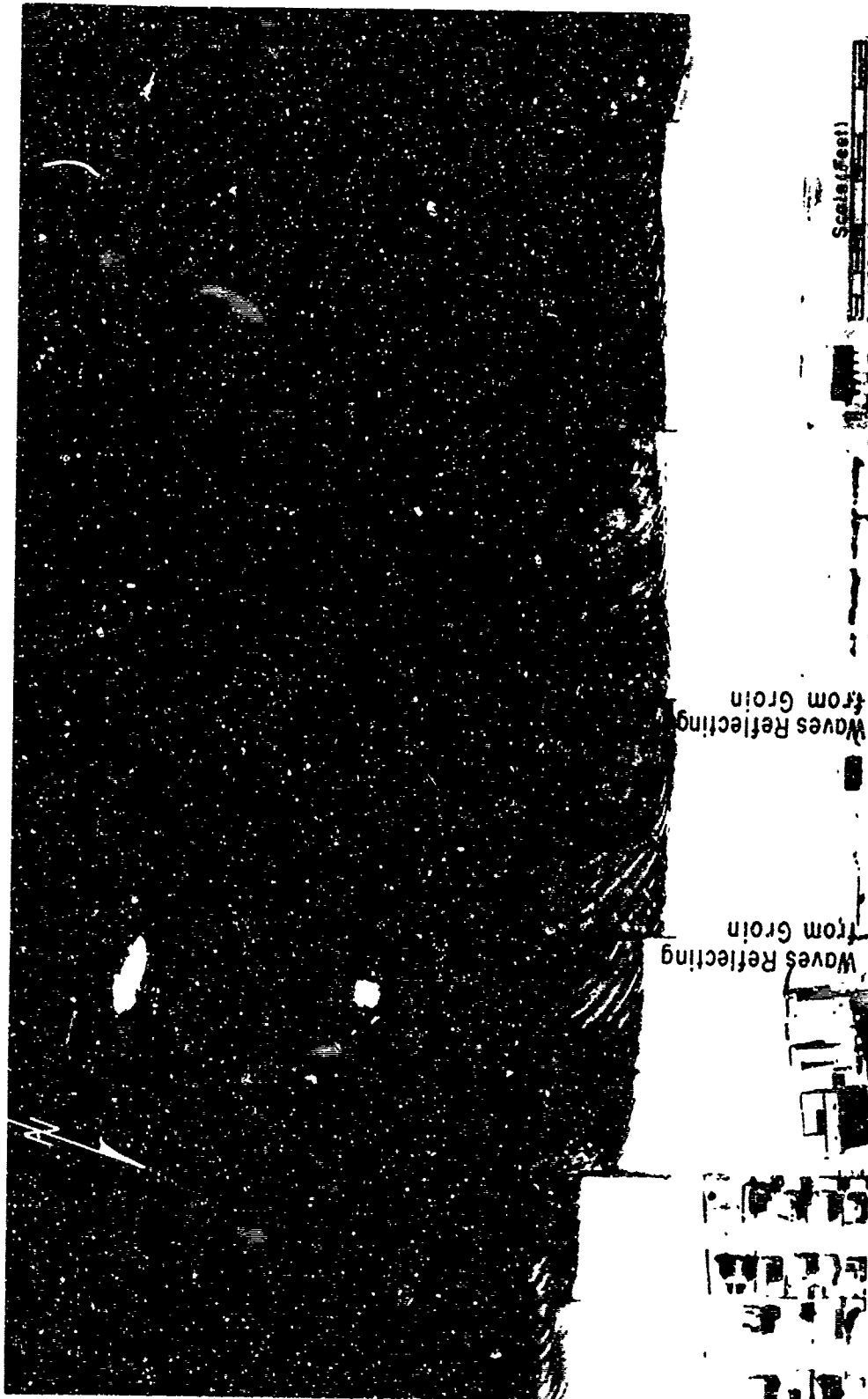


Figure 27. Near Rockaway Beach, Long Island, New York. Photo taken 17 March 1962. Waves can be seen moving shoreward at an angle to the beach and then being reflected by the groins and beach (Courtesy of U.S. Navy).



Figure 28. Waves diffracting around breakwater tips off Channel Islands Harbor, California. Photo taken June 1960 (U.S. Army, Coastal Engineering Research Center, 1973).



Figure 29. Long-period swell moving past breakwater and into mouth of Ventura Marina, California. Photo taken 16 October 1972.



Figure 30. California coast south of Point Mugu. Photo taken 2 April 1968.  
Waves are undergoing large amount of refraction.



Figure 31. Bald Head Shoal on the east bank of the mouth of the Cape Fear River, North Carolina. Photo taken 1 November 1971. A train of waves approaching the coast from below the photographed area has its crests bent due to refraction; the waves eventually cross and form rhomboidal patterns over the shoal area (Courtesy of U.S. Air Force).

The wave pattern is caused by a single train of waves coming from directly below the bottom of the photo. The part of the wave train arriving at A continued moving shoreward in the direction shown by the arrow. However, the part of the wave train that has arrived at B has been refracted by the effects of the shoal so that it is now moving toward the east. The interesting result is seen shoreward of the two arrow tips--the crossing wave crests form rhomboidal patterns. Construction of a refraction diagram for the area would produce crossed orthogonals.

The oblique photo in Figure 32 was taken during a rising tide along the outer banks of North Carolina at Drum Inlet; therefore, flood currents are flowing from the Atlantic Ocean into Core Sound. Low waves are approaching from the Atlantic Ocean moving over the shoal outside of the mouth of the inlet. The waves steepen as they cross the shoal and then flatten out again and continue into the throat of the inlet where tidal currents, traveling in the same direction, cause the wave steepness to decrease. After the waves move through the inlet and out of the current their steepness increases as they continue to move over the shoal area inside the inlet.

Figure 33 is a photo of the same inlet during a falling tide. An ebb current flows from Core Sound, out through Drum Inlet, and into the Atlantic Ocean. The currents moving out of the inlet aid in pressing the breaker line outward. This seaward shift of the breakers is due to the waves moving in a direction opposite to that of the current, thereby increasing the wave steepness and producing breaking earlier than would occur over the offshore bars in the absence of an ebb current.

#### 9. Consistency of Wave Conditions.

The aerial photos of waves examined in this study generally display a highly organized, though often complex, appearance. There is little evidence of the "random sea" often mentioned in discussions of ocean waves. The photos, show the wave geometry only for an instant in time; therefore, the much discussed randomness of ocean waves may result from irregular changes in the wave patterns as they develop in time. To investigate this possibility, the same coastal area was photographed several times within the same hour on 30 April 1973 with the support of the NASA Earth Observation Aircraft Program. Typical results are shown in Figures 34 through 37. All four photos show the north end of Island Beach State Park, New Jersey, and all reveal two distinct wave trains. Ship waves appear in various parts of all photos and at least one area of ship waves as well as two trains of ocean waves are annotated in each photo. A timespan of 42 minutes elapsed between the photos in Figures 34 and 37.

In each figure, a long-period swell, A, can be seen approaching the coast from the upper left of the photo. A second wave train, comprised of local sea, B, can also be observed in each figure. The train of sea waves is moving from right to left across the photos.



Figure 32. Oblique photo of Drum Inlet, North Carolina, taken 16 February 1972 during high tide. As waves move into the inlet, their steepness decreases so that they do not break but are allowed to pass through into Core Sound.



Figure 33. Oblique photo of Drum Inlet, North Carolina, taken 20 January 1972 during low tide. Breaker line is being pressed seaward by ebb current.

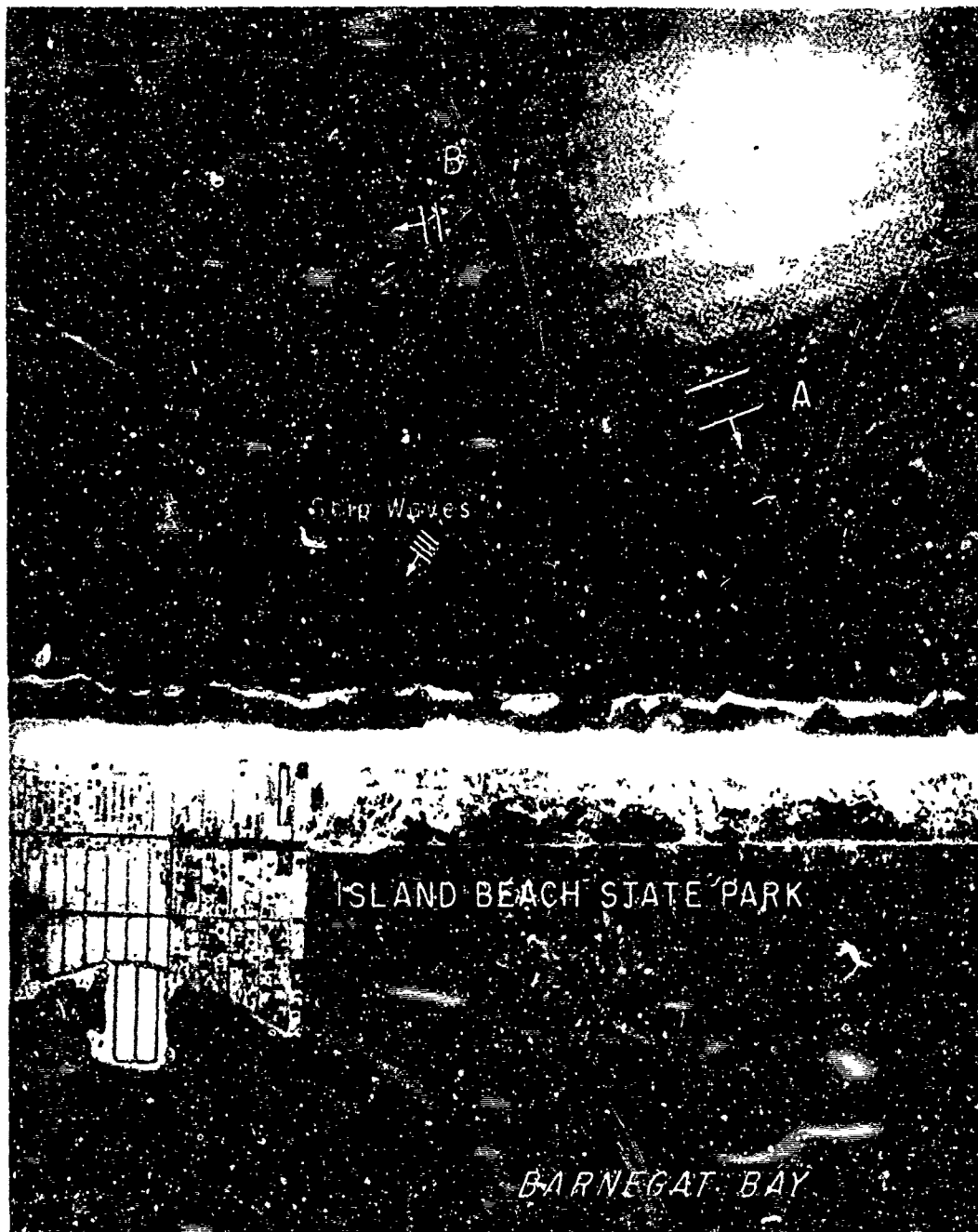


Figure 34. Wave field at 1105 hours EST, 30 April 1973, off Island Beach State Park, New Jersey (Courtesy of NASA).



Figure 35. Wave field at 1120 hours EST, 30 April 1973, off Island Beach State Park, New Jersey (Courtesy of NASA).

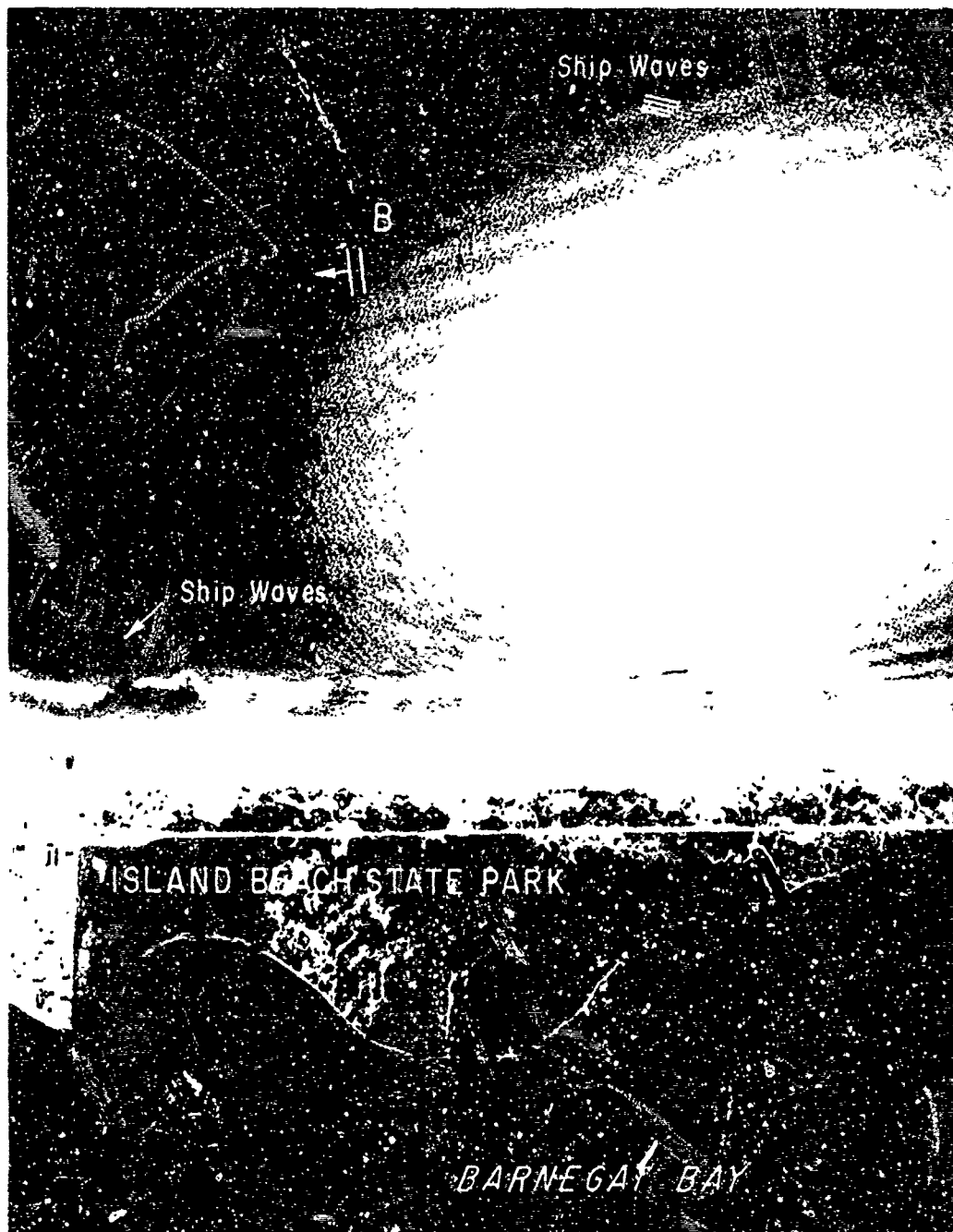


Figure 36. Wave field at 1131 hours EST, 30 April 1973, off Island Beach State Park, New Jersey (Courtesy of NASA).



Figure 37. Wave field at 1147 hours EST, 30 April 1973, off Island Beach State Park, New Jersey (Courtesy of NASA).

A tracing of wave crests from the photos in Figures 34 through 37, is shown in Figure 38. The number corresponding to the figure from which the wave crests were taken is located at the ends of the traced crestline. The appearance of all crestlines in Figure 38 is that they could have been obtained from a single photo representing only one instant in time. Each of the three groups of crestlines has nearly the same alignment. This indicates that for the 42-minute timespan during which these photos were taken, the wave systems, other than ship waves, remained nearly constant. This sequence of photos give little support to the concept of a random sea.

## VI. COMPARISON OF PHOTOGRAPHS WITH WAVE RECORDS

Figure 39 is a photo of the CERC Prototype Experimental Groin (PEG) site near Point Mugu, California, taken at 1334 hours Pacific Standard Time (PST). An inspection of the offshore area reveals three distinct wave trains. A train of long-period swell, A, is barely visible offshore due to its low wave height in that area; however, the same swell dominates the breakers. A second train of swell, having a shorter wavelength, B, approaches the coast from the upper right of the photo. This train is also contributing some energy to the breakers at D. A local sea, C, is moving in a direction almost normal to the coastline. Using wavelengths measured from Figure 39 and estimates of local water depths, a wave period was calculated for each of the three wave trains. For wave trains A, B, and C, the calculated wave periods were 13.4 seconds (0.075 hertz), 6.4 seconds (0.156 hertz) and 3.0 seconds (0.333 hertz), respectively.

Wave energy spectra from three bottom-mounted pressure gages located offshore from the PEG site in about 30 feet of water is shown in Figure 40. The displayed spectra were obtained from 17-minute wave records which began at 1340 hours PST on 21 May 1972. The spectra for frequencies greater than 0.333 have not been plotted since pressure correction in that region of the spectrum produces questionable results.

The spectra exhibited in Figure 40 are bimodal, with spectral peaks near the calculated frequencies of A and C. The energy spectra do not reveal any significant peak near the frequency calculated for wave train B in Figure 39. This observation is puzzling since B is visible offshore and can be seen participating in the breakers at D. However, absence of a significant peak in the energy spectra for B may be explained by the fact that the wave gage is located in water 30 feet deep.

Using the nomograph presented by McClenan (1975), the relative wave height ( $H/H_0$ ) was determined a function of depth and is shown in Figure 41 for each wave train. The relative wave height is a ratio between the wave height (H) at a given depth and the deepwater wave height ( $H_0$ ). Using the wave periods and directions of wave travel derived from Figure 39 and the assumption that the bottom contours are straight and parallel

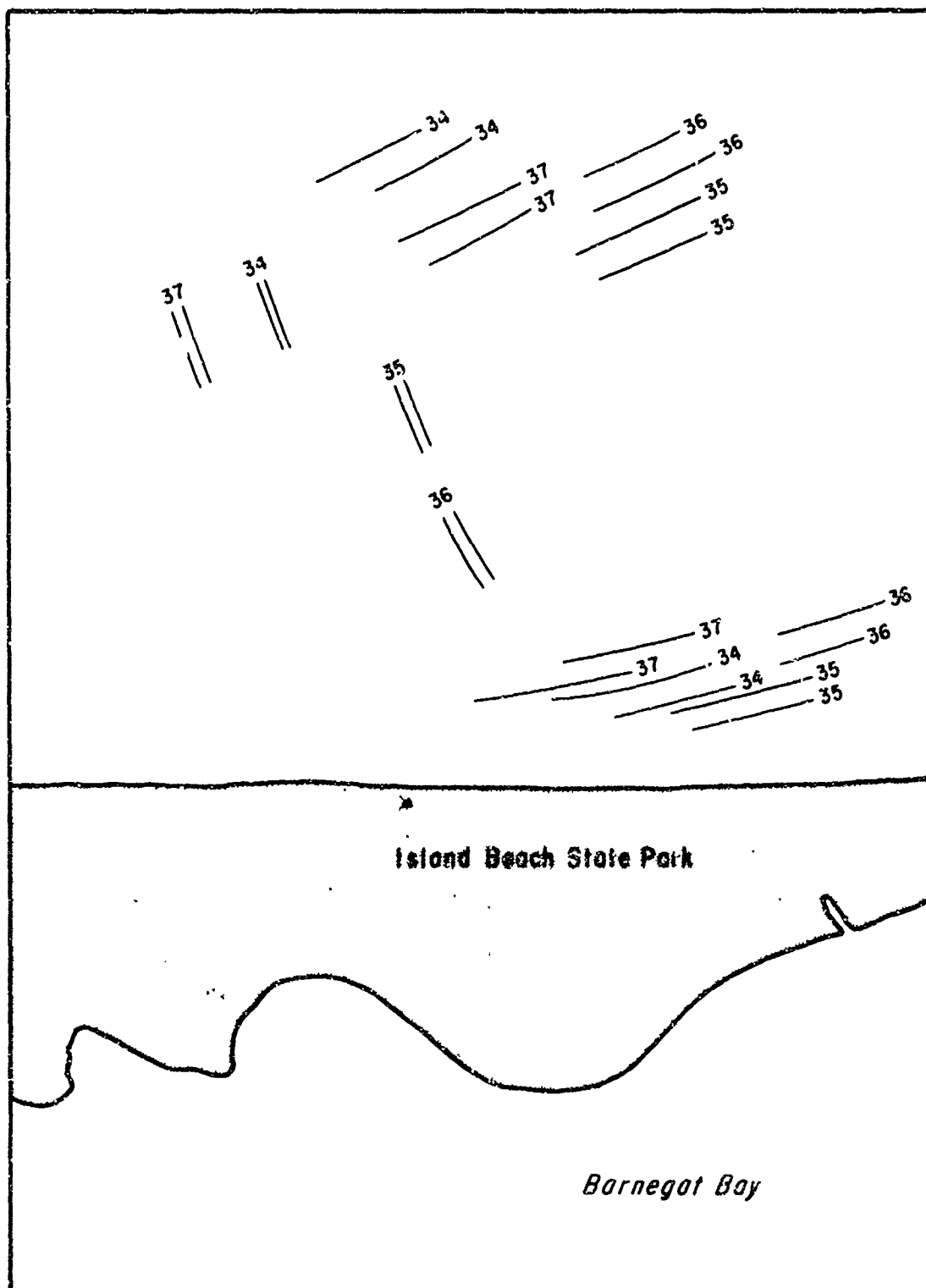


Figure 38. Trace of wave crests revealed in Figures 34 through 37.

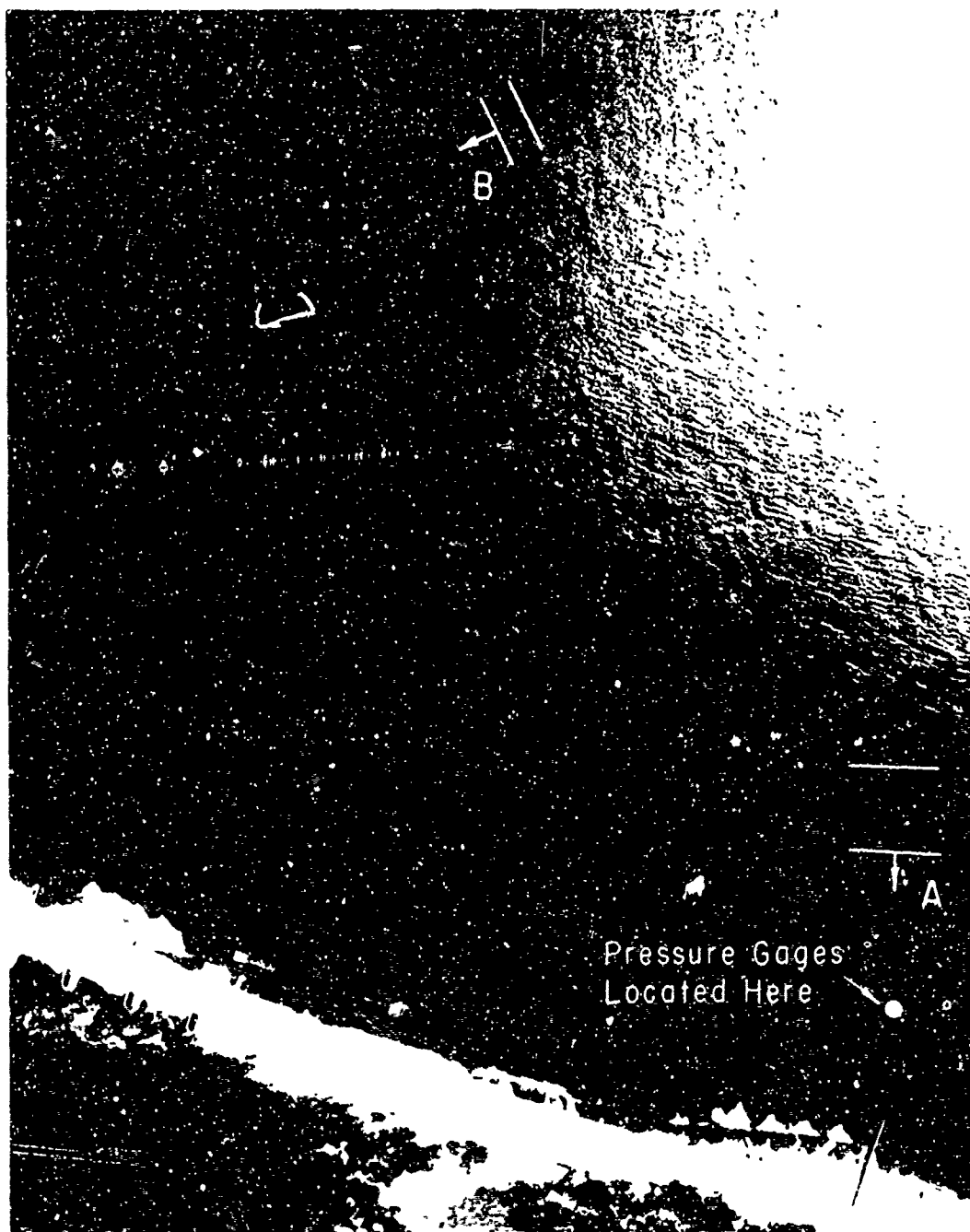


Figure 39. CERC Prototype Experimental Groin Site near Point Mugu, California. Photo taken at 1346 hours PST, 21 May 1972. Wavelengths measured between wave crests near A, B, and C were 505, 207, and 45 feet, respectively (Courtesy of NASA).

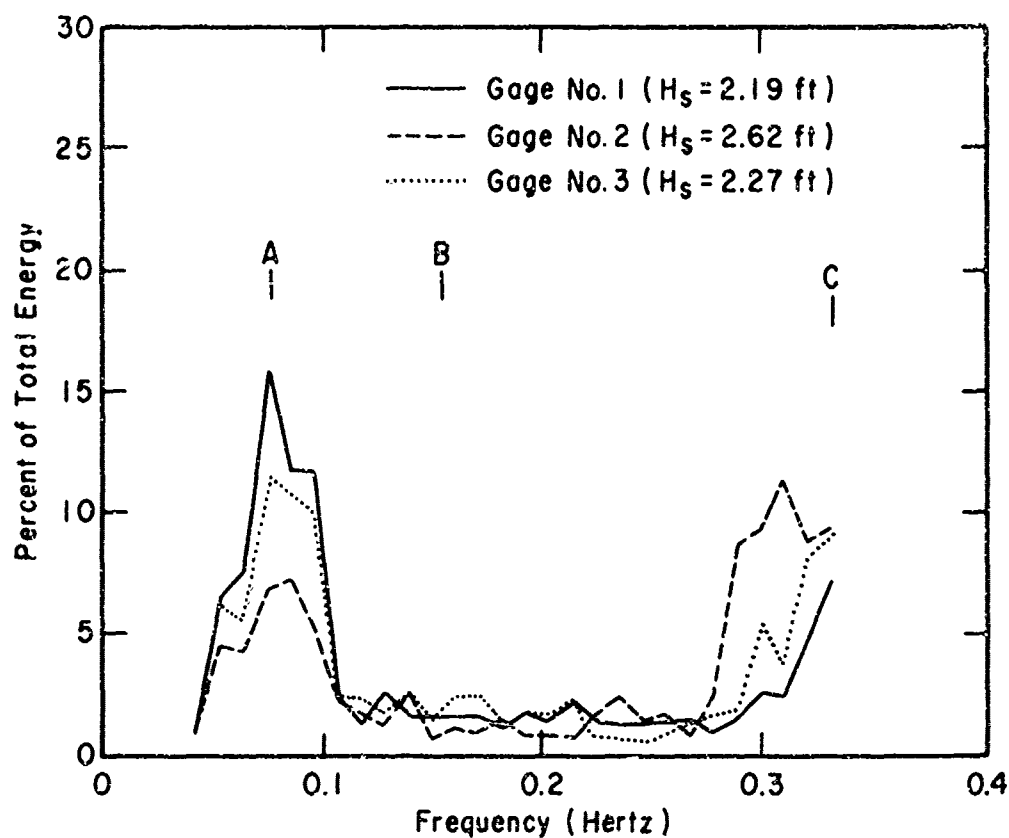


Figure 40. Energy spectra for three pressure gages offshore from the PEG site. Spectra were derived from 17-minute wave records begun at 1340 hours PST on 21 May 1972. A, B, and C represents frequencies estimated from wavelengths measured from Figure 39. The spectra shown here have been compensated for hydrodynamic attenuation due to submergence of the gage.

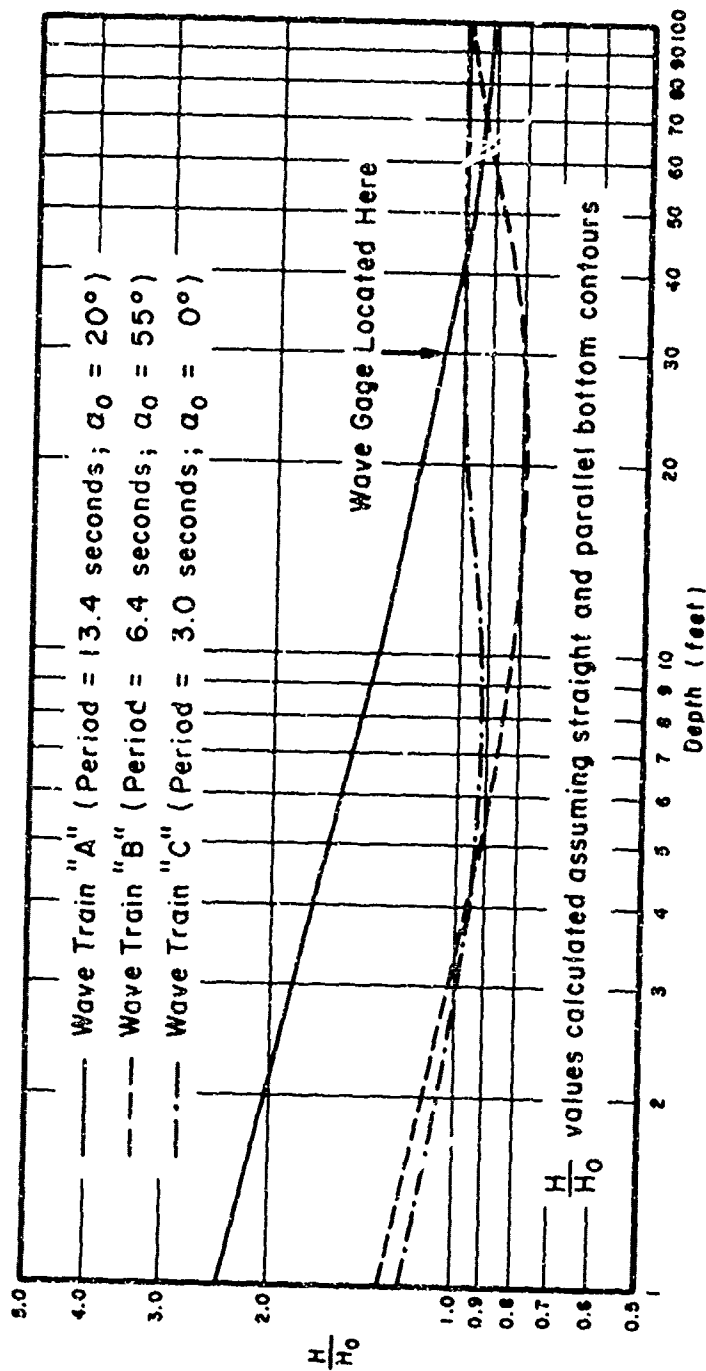


Figure 41. Relative wave height versus depth for three wave conditions produced from Figure 39. The relative wave height was obtained by incorporating both refraction and shoaling effects assuming straight and parallel contours.  $\alpha_0$  is the estimated deepwater angle between the wave crest and the shoreline.

within the area of interest, the effects of both shoaling and refraction were incorporated into the  $H/H_0$  versus depth curve for each wave train.

The water depth at the wave gage during the wave record was 30 feet (shown in Fig. 41). At that depth, the height of the waves in train A has increased slightly over the height in deep water; wave train C, with a very short wavelength, has not yet felt bottom sufficiently to cause a significant effect on the wave height. However, the height of wave train B has lowered about 20 percent due to the effects of shoaling and refraction. The photo in Figure 41 also indicates that at a depth of 3.3 feet, the wave height of B increased again to its original height in deep water. The increase in the wave height of C as the wave approaches the shore, indicates that C did increase enough to contribute some energy in the breakers as seen at D in Figure 39.

It may not be unreasonable to find that the most significant spectral peak obtained from analysis of wave records from an offshore gage does not necessarily represent the wave train dominating the breakers on shore (Figs. 39, 40, and 41).

Figure 42 shows wave conditions near Jennette's Pier, Nags Head, North Carolina, at 0949 hours EST on 13 February 1973. The wave train, A, is easily detected; however, there appears to be another wave train with about the same wavelength. This second wave train (direction shown at B) is almost completely masked due to its relatively low height and poor photographic conditions.

The energy spectra produced from wave records taken 3 hours before and after the photo in Figure 42 are shown in Figure 43. The wave gage is located at the end of the pier (Fig. 42). Each of the two spectra has three distinct peaks located at nearly the same frequency; therefore, it may be assumed that the sea state remained reasonably constant between the two wave records. Wave periods calculated with wavelength measurements from Figure 42 varied between 12.5 (0.08 hertz) and 15.5 seconds (0.065 hertz). This band of periods includes the highest peaks in both spectra since both peaks occurred near 14.4 seconds (0.070 hertz). Wave trains corresponding to the two other spectrum peaks, near 0.15 and 0.23 hertz, are not clearly visible in the offshore area. A close examination of the photo in Figure 42 indicates long flat troughs and short-peaked crests, more like solitary than sinusoidal waves. To describe a wave profile of this type by sinusoidal functions would require a series expansion consisting of many terms; also, the frequencies of the second and third spectrum peaks are roughly two and three times the frequency of the largest peak. Exact correspondence is not to be expected because of the finite resolution (approximately 0.01 hertz) in these spectra.

The photo in Figure 44 was taken at 1020 hours EST, 13 February 1973, over Johnny Mercer's Pier at Wrightsville Beach, North Carolina and shows a complex wave crest structure. This is, in part, a result of the



Figure 42. Jennette's Pier at Nags Head, North Carolina. Photo taken at 0949 hours  
EST, 13 February 1973. Wavelengths measured for the wave crests near  
A and B ranged from 430 to 470 feet (Courtesy of NASA).

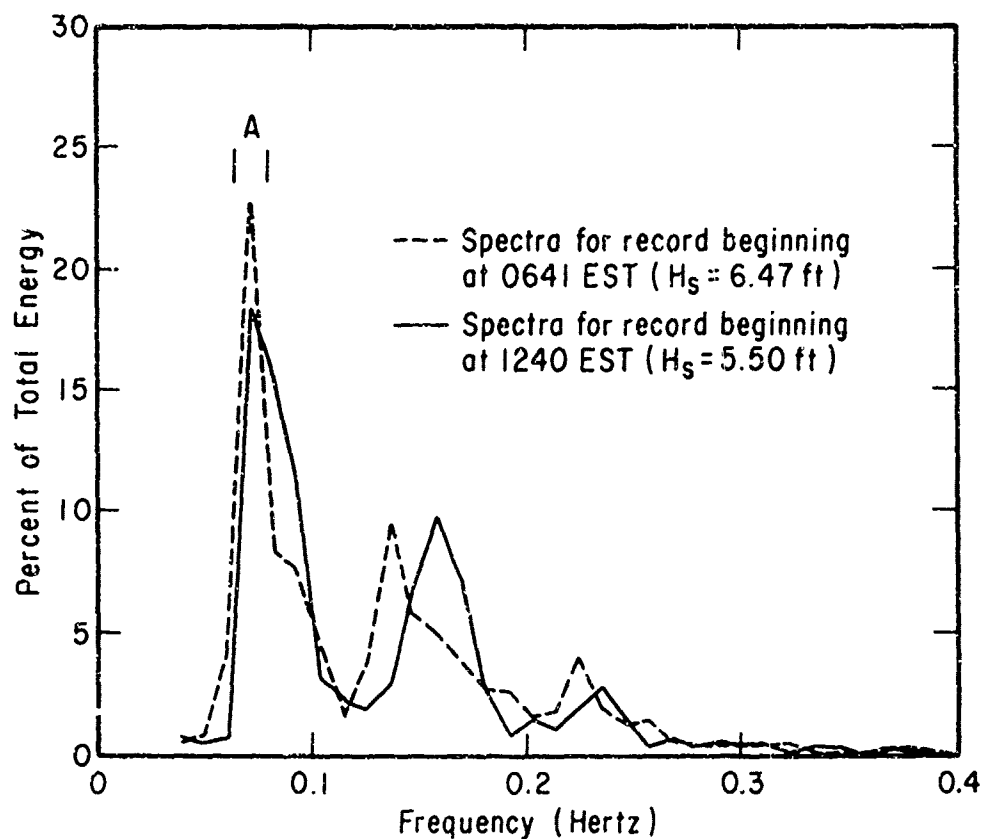


Figure 43. Energy spectra for wave gage on Jennette's Pier at Nags Head, North Carolina. Photo taken 13 February 1973. Spectra were derived from 17-minute wave records at 0641 and 1240 hours EST. Frequencies estimated from wavelengths measured from Figure 42 are represented at A.

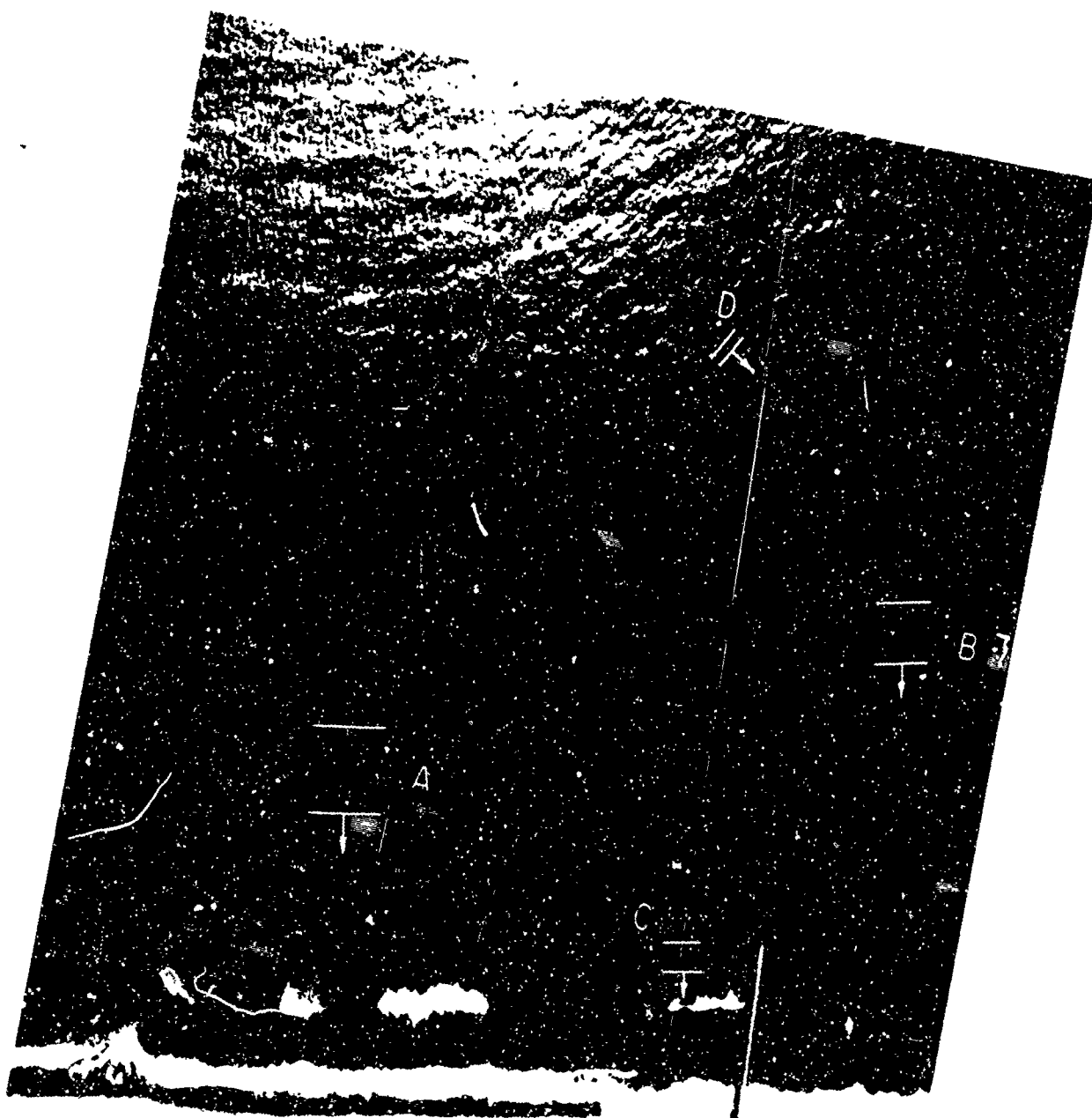


Figure 44. Johnny Mercer's Pier at Wrightsville Beach, North Carolina. Photo taken at 1020 hours EST, 13 February 1973. Wavelengths measured for the wave crests indicated at A, B, C, D, and E are 342, 233, 109, 47, and 32 feet, respectively (Courtesy of NASA).

low wave heights at the time the photo was taken. Low waves generally have gently sloping profiles which result in poor photographic contrast between crests and troughs. The figure also shows wave energy scattered over a wide frequency range, which makes selection of dominant frequencies difficult. Some wave crests and directions identifiable in various parts of the photo are indicated in Figure 44. The wave periods (frequencies) estimated from wavelengths measured at A, B, C, D, and E are 12.47 (0.0802), 7.86 (0.127), 5.52 (0.181), 3.03 (0.330), and 2.50 seconds (0.400 hertz), respectively. The offshore area does not seem to be dominated by any single wave train; however, the breaker zone is visibly dominated by a long-period wave aligned nearly parallel to the beach at the time of breaking.

The energy spectra for two 17-minute wave records begun at 0641 and 1240 hours EST on 13 February 1973 are plotted in Figure 45. The wave gage which produced these records is located on the end of Johnny Mercer's Pier (Fig. 44). As expected, the spectra show a sizeable spread of energy over the frequencies ranging from 5 to 10 seconds (0.1 to 0.2 hertz). The highest peak occurs at a frequency of about 12.5 seconds (0.08 hertz), which corresponds to the estimated period of the long, low waves dominating the breaker zone in Figure 44.

## VII. DISCUSSION

More than 40,000 photos have been examined for information about wave conditions in coastal waters. In a photo taken at an elevation of less than 2,000 feet, the sea often appears to be a random sequence of *humps* and *hollows* with little or no organized structure; at elevations of 5,000 feet and greater, the general impression is one of highly organized but complex patterns. Generally, it is possible to distinguish from two to five distinct wave trains. When the water is deep enough, relative to the wavelength for refraction to be unimportant, most waves appear to be long-crested (crest lengths 10 to 20 times the wavelengths); the disappearance of a wave crest in a photo may depend as much on shortcomings in the photography as physical reality. These long-crested wave trains appear to move through each other. When two wave trains have nearly the same wavelength but different directions of propagation, they reinforce or cancel each other in regular patterns. When only a small part of the resulting pattern is seen, the dominant impression is one of short-crested waves or randomness. When many repetitions of the pattern are seen at once, usually the result of viewing the scene from a greater altitude, the eye readily filters out the breaks in wave trains resulting from the cancellation, and the dominant impression is one of intersecting but well organized long-crested waves.

In viewing photos taken at 5,000 feet or higher, the direction of each wave train appears to be well determined within a few degrees, and to remain constant for periods of at least an hour. No evidence has been found for the type of directional spreading reported by Chase, et al. (1957), Cote, et al. (1960), and Longuet-Higgins, Cartwright, and Smith (1963).

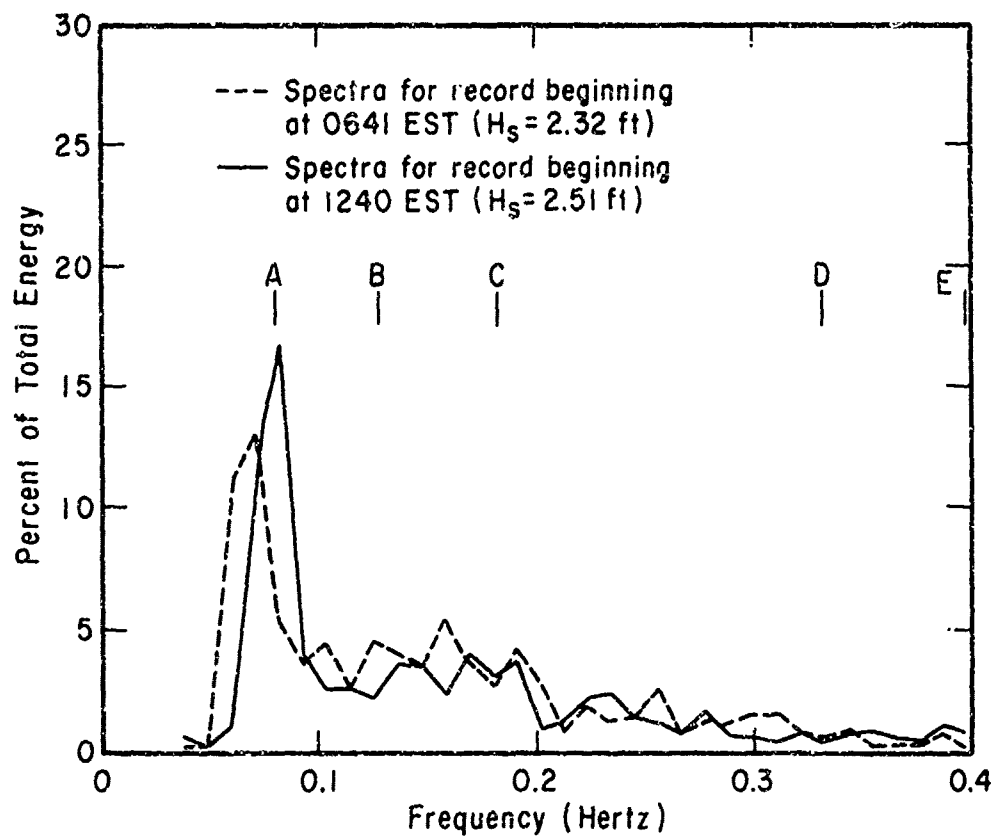


Figure 45. Energy spectra for wave gage at Johnny Mercer's Pier, Wrightsville Beach, North Carolina. Spectra were derived from 17-minute wave records at 0641 and 1240 hours EST, 13 February 1973. A, B, C, D, and E represent frequencies estimated from wavelengths measured from Figure 44.

In shallow water the photos show the expected evidence of refraction, i.e., diffraction and reflection from breakwaters and sometimes from beaches. Bending of individual wave crests by as much as  $60^\circ$  due to refraction or diffraction is sometimes observed.

Some photos show cylindrical wave-crest patterns with small rocks or other protrusions from the bottom near the center of the pattern. This process may be compared to the scattering of light by small particles in the atmosphere. It differs from optical scattering, however, in that the outgoing waves are shorter than the incoming waves. This process is rarely discussed in textbooks dealing with water waves.

One notable feature of most aerial photos of waves in the coastal zone is the pronounced change in the wave spectrum in the last mile of wave travel toward the beach. Low swell, approaching the beach along a ray nearly normal to the shore possibly because of refraction even farther from shore, is amplified by shoaling and often dominates the breakers, even when the same wave train could hardly be detected against the background of wind waves a mile from shore. The shorter wind waves, usually most prominent a mile from shore, may be traveling in almost any direction. Consequently, they often travel along rays nearly parallel to the shore. If they approach the shore at all, they are often so attenuated by refraction as to be unrecognizable in the breaker zone.

With the recent expanded interest in remote sensing and the development of optical transform techniques, it is often suggested that a two-dimensional wave number spectrum, effectively a directional spectrum, can be obtained from photos by optical Fourier transforms (Stilwell, 1969; Stilwell and Pilon, 1974). The optical transform technique may be useful in deep water where the wave speed is independent of position, and the processes of refraction, diffraction, reflection, and scattering can be neglected; however, the interpretation of optical transforms of photos of shallow water waves presents many problems. The compression of waves by shoaling would lead to a broad band of wave numbers for a single frequency. The bending of wave crests by refraction will yield a wide spread of directions for incoming waves, in direct contrast to the appearance in the photos.

Most waves examined in this study were photographed in relatively clear weather near coastlines of the United States. The well organized character of the waves displayed in the photos may be characteristic only of fair weather conditions and that storm waves, which could not be photographed because of low cloud cover, are more chaotic and less organized. Perhaps this cannot be answered by photography, but airborne imaging radar may provide a definitive answer. It is possible that coastal topography forms a series of wave traps with certain combinations of wave frequency and direction being preferred for each tide condition at each coastal location.

This may ultimately be resolved by shore-based radar which can provide suitable wave imagery under a wide range of weather conditions and on a more frequent basis than is feasible by aerial photography.

#### VIII. SUMMARY AND CONCLUSIONS

Photos of waves examined in this investigation characteristically show from two to five distinct wave trains. Where the effects of shoaling and currents can be neglected, each wave train appears to be nearly discrete in wavelength and direction of propagation. In shallow water the wave trains remain distinct but the wave crests are curved by refraction and diffraction. Cylindrical wave-crest patterns radiate outward from rocks or other bottom protrusions which penetrate the surface whenever quasi-long-crested waves approach from the open sea.

Although the photos used in this report were obtained under fair weather conditions and, therefore, do not provide conclusive evidence about the appearance of storm waves, they do show clearly that some widely used conceptual models of wave behavior are not adequate for solving coastal problems. In particular, those models which regard ocean waves as random phenomena and whose direction and frequency can be specified only in statistical terms do not correspond to the data revealed by these photos.

Conceptual models of ocean waves widely used in engineering design which seek to characterize each wave observation by a single value of wave height, wave period and wave direction are also inadequate.

Considering the conditions shown in the photos, characterization of the wave field by the sum of a small number of monochromatic wave trains appears to be a better approximation than by any of the published spectrum forms, e.g., as proposed by Pierson and Moskowitz (1964), Bretschneider (1963), and Hasselmann, et al. (1973).

This study suggests that new conceptual models of ocean waves are needed to provide a more accurate description of the actual wave field for the solution of many engineering problems.

# LITERATURE CITED

- BRETSCHNEIDER, C.L., "A One-Dimensional Gravity Wave Spectrum," *Ocean Wave Spectra*, Prentice-Hall, Englewood Cliffs, N.J., 1963, pp. 41-56.
- CHASE, J., et al., "The Directional Spectrum of a Wind-Generated Sea as Determined from Data Obtained by the Stereo Wave Observation Project," College of Engineering, New York University, July 1957.
- COTE, L.J., et al., "The Directional Spectrum of a Wind Generated Sea as Determined from Data Obtained by the Stereo Wave Observation Project," *Meteorological Papers*, Vol. 2, No. 6, College of Engineering, New York University, June 1960, 88 pp.
- CROOKE, R.C., et al., "Beach Profile Determination from Timed Aerial Photography," Series 29, Issue 48, Institute of Engineering Research, University of California, Berkeley, Calif., June 1951.
- DICKERSON, L.A., "Stereogrammetric Wave Measurement," *The Bulletin of the Beach Erosion Board*, Vol. 4, No. 4, Oct. 1950, pp. 40-45.
- EMERY, K.O., "Wave Patterns of Southern California," *Journal of Marine Research*, Vol. 17, 1958, pp. 133-140.
- EMERY, K.O., "An Aerial Study of Hawaiian Wave Patterns," *Pacific Science*, Vol. 17, No. 3, July 1963, pp. 255-260.
- HARRIS, D.L., "Characteristics of Wave Records in the Coastal Zone," *Waves on Beaches and Resulting Sediment Transport*, Academic Press, New York, 1972, pp. 35-40.
- HASSELMANN, K., et al., "Measurement of Wind-Wave Growth and Swell Decay During the Joint North Sea Wave Project (JONSWAP)," *Deutsches Hydrographisches Institut*, Hamburg, 1973, 95 pp.
- JOHNSON, J.W., "Progress Report Wave-Velocity Method of Determination by Aerial Photographs," Technical Report No. 155-10, Department of Engineering, University of California, Berkeley, Calif., Oct. 1949.
- KINSMAN, B., *Wind Waves*, Prentice-Hall, Englewood Cliffs, N.J., 1965, 675 pp.
- KORSHUNOV, U.S., "Oblique Wave Photography with a Single Survey Camera from an Airplane," *Soviet Oceanography*, Vol. 28, No. 2, 1963, pp. 56-58.
- LONGUET-HIGGINS, M.S., CARTWRIGHT, D.E., and SMITH, N.D., "Observations of the Directional Spectrum of Sea Waves Using the Motions of a Floating Buoy," *Ocean Wave Spectra, Proceedings of a Conference*, Prentice-Hall, Englewood Cliffs, N.J., 1963, pp. 111-132.

- MARKS, W., and RONNE, F.C., "Aerial Stereo-Photography and Ocean Waves," *Photogrammetric Engineering*, Vol. 21, No. 1, Mar. 1955, pp. 107-110.
- McCLENAN, C.M., "Simplified Refraction," Unpublished report, 1975  
(to be published as CERC TM).
- MOFFITT, F.H., "The Photogrammetry of Depth Determination by Wave Velocity Method from Aerial Photographs," Series 74, Issue 4, Institute of Engineering Research, University of California, Berkeley, Calif., Sept. 1953.
- PIERSON, W.J., and MOSKOWITZ, L., "A Proposed Spectral Form for Fully Developed Wind Seas Based on the Similarity Theory of S.A. Kitaigorodskii," *Journal of Geophysical Research*, Vol. 69, No. 24, Dec. 1964, pp. 5181-5190.
- POLCYN, F.C., BROWN, W.L., and SATTINGER, I.J., "The Measurement of Water Depth by Remote Sensing Techniques," Report No. 8937, University of Michigan, Ann Arbor, Mich., Oct 1970.
- POLCYN, R.C., and SATTINGER, I.J., "Water Depth Determination Using Remote Sensing Techniques," *Proceedings of the Sixth International Symposium on Remote Sensing of Environment*, Vol. II, Oct. 1969, pp. 1017-1028.
- SAWYER, D.W., "Preliminary Report on the Determination of Water Surface Profiles," Report No. 103-49, U.S. Naval Photographic Interpretation Center, Washington, D.C., June 1949.
- SCHUMACHER, A., "Results of Exact Wave Measurements (by Stereo-Photogrammetry) with Special Reference to More Recent Theoretical Investigation," *Proceedings of the National Bureau of Standards Semicentennial Symposium on Gravity Waves*, National Bureau of Standards Circular 521, Washington, D.C., 1952, pp. 69-78.
- STILWELL, D., Jr., "Directional Energy Spectra of the Sea from Photographs," *Journal of Geophysical Research*, Vol. 74, No. 8, Apr. 1969, pp. 1974-1986.
- STILWELL, D., Jr., and PILON, R.O., "Directional Spectra of Surface Waves from Photographs," *Journal of Geophysical Research*, Vol. 79, No. 9, Mar. 1974, pp. 1277-1284.
- U.S. NAVAL PHOTOGRAPHIC INTERPRETATION CENTER, Photographic Interpretation Technical Bulletin, NAVWEPS 10-35TB-505, Washington, D.C., Oct. 1960.
- U.S. NAVAL PHOTOGRAPHIC INTERPRETATION CENTER, "Underwater Depth Determination," Report No. 46, Washington, D.C., Oct. 1944.

WARD, H.A., "A Method of Separating Multiple Systems of Ocean Waves for Detailed Study of Direction and Other Properties," *The Bulletin of the Beach Erosion Board*, Vol. 6, No. 3, July 1952, pp. 1-13.

ZDANOVICH, V.G., and SHARIKOV, Y.D., "Wave Height Estimation Based on Single Perspective Aerial Photographs," *Oceanology*, Vol. 6, 1966, pp. 294-300.